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Operation CASTLE

PACIFIC PROVING GROUNDS

March – May 1954

Project 1.6

WATER-WAVE MEASUREMENTS (U)

Issuance Date: October 19, 1959

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FOREWORD

This report is one of the reports presenting the results of the 34 projects participating in the Military Effects Tests Program of Operation Castle, which included six test detonations. For readers interested in other pertinent test information, reference is made to WT-934, Summary Report of the Commander, Task Unit 13, Military Effects, Programs 1-9. This summary report includes the following information of possible general interest: (1) an overall description of each detonation, including yield, height of burst, ground zero location, time of detonation, ambient atmospheric conditions at detonation, etc., for the six shots; (2) discussion of all project results; (3) a summary of each project, including objectives and results; and (4) a complete listing of all reports covering the Military Effects Tests Program.

ABSTRACT

This report covers studies of water-surface waves generated within Bikini Lagoon by nuclear detonations. Measurements of wave heights were obtained from underwater pressure-time instrumentation. In addition, surveys of inundation levels on land areas were made. By these methods the heights and nature of the waves generated were determined. These waves were sufficiently high to produce significant damage to shore installations at distances of 14 miles. The magnitude of waves that might result from such explosions on deeper shelves, or in deeper water, cannot be reliably estimated from these results.

A partially empirical equation is examined that predicts the observed first-crest wave heights. First-crest height was indicated to decay inversely proportional to R, the range from zero point. The first-wave height-range product scales as a function of charge weight to the one-half power over the yield range of nuclear tests to date. The water depth effect in the region of generation could not be resolved, but the evidence indicates that the first-wave height varies directly as water depth to the 0.7 power. The generated waves contained an extremely small percentage of charge energy.

It is recommended that further study of the mechanism of wave generation be made, aimed toward permitting the evaluation of the wave-making capabilities of a large range of explosions under previously unexplored geometries. Pending such a study, it is recommended that careful estimation of the wave generation possibilities, including scaled model tests with a small nuclear detonation, be undertaken before the hazard of waves from high-yield devices be eliminated from plans for near-water thermonuclear experiments under geometries (particularly water depth) that differ greatly from those studied. Additional data is required of the close-in wave-generating processes associated with nuclear tests.

CONTENTS

TABLES

Chapter I
INTRODUCTION

The original objectives of Project 1.6 were curtailed by the emergence of the serious problem of radioactive fallout. This affected the project in two ways: (1) accessibility to the islands and parts of the lagoon for purposes of conducting the inundation surveys and maintaining instruments was greatly reduced and (2) project personnel undertook to attack the important problem of fallout surveys by oceanographic methods. Underwater counters, samplers and other equipment were hurriedly constructed and the ATF 86 (USS Sioux) was outfitted as a survey vessel. Surveys were conducted for Shots 5 and 6. Field investigation, preliminary and final analysis, and reporting of the fallout data were undertaken on a priority basis.

These matters skeletonized Project 1.6 personnel and greatly delayed the reporting of results.

In the period between the Interim Test Report and this final Weapon Test Report, Scripps Institution engaged in two additional operations, Wigwam and Redwing. During Wigwam an entirely different geometry was explored. For Redwing, more instruments were employed with stronger cables; additional self-contained recorders ("turtles") were installed close to the detonations; a different range of device yields was documented; and the inundation surveys and instrument maintenance were unhampered by the serious radiation hazard that was attendant to Operation Castle. In addition, following the Castle tests a number of important theoretical and experimental advances took place (References 3, 4, 5, 11).

As a result of these factors, more and better data is now available than that reported upon within, and theories are better able to accommodate it. The authors believe that an effort to extract detailed conclusions based solely on the Castle data is unrealistic. The effort of this report, therefore, is to present a thorough documentation of results, together with the indicated conclusions, and to leave the detailed interpretation of the Castle results for a synergistic inclusion with those of Redwing.

1.1 OBJECTIVES

The purpose of Project 1.6 was to obtain data directed toward an understanding of the mechanism of wave generation by disturbances. It is hoped that understanding eventually will be attained that will permit the rational prediction of waves produced by disturbances occurring under the environmental conditions of depth, motion, and geometry previously unexplored.

This result was not expected from the work of Project 1.6 alone, because of the poor opportunity to observe processes in the central region, the complexity and relatively small depth and size of the site, and the small range of geometric conditions. Hence, the results of Project 1.6 can be considered as highly empirical results, applicable to conditions that depart only slightly from those under which the data were taken. Thus, the Project 1.6 results can be considered mainly as documentation.

Successive documentation, leading eventually to basic understanding, is of great importance to the military for reasons of which the following are examples: surface waves are effective and efficient mechanisms for the long-range transfer and sudden release of energy against obstacles and the shore; waves generated in harbors may constitute a serious source of damage to shore installations; moored and docked vessels, drydocks, locks, dams, bridges, airfields, sea mines and submarine cables may be more affected by sea waves than by blast effects; and under certain deep-water geometries of detonation, megaton-range weapons may give rise to tsunami-like waves that can produce serious damage to extensive coastal areas.

1.2 BACKGROUND AND THEORY

The status of theory and background will be discussed under three somewhat separable processes.

1.2.1 Wave Propagation. Pertinent wave-propagation theory exists that is adequate for the understanding of some of the results. In a complex site such as Bikini Lagoon, the effects of reflection, diffraction, rectification, and breaking can be understood only in a general way. Geometrical approaches that can handle the first-order effects of complex topography on waves exist (References 1, 6, and 7), provided the wave height is not large in comparison with the depth. The excursion of high-amplitude waves over relatively shallow bottom can be only qualitatively described at present. Certain experimental work (Reference 3) has been completed in 1955, however, and parts of this work will be applied to the Castle-Redwing results.

1.2.2 Wave Generation. Considerable empirical information exists covering a wide range of high-explosive experiments on wave generation. These cover only cases of simple geometry. A further study of high-explosive tests in comparison with nuclear results may reveal dependable methods of application of the high-explosive data to explosions of thermonuclear magnitude. However, at present, the applicability of high-explosive model tests is questionable on two bases: primarily, there is no assurance of the similarity of atomic and chemical explosions at an interface; secondly, complete model explorations of the variety of natural geometries of military or test sites may be impractical. These sites normally have irregularities that may profoundly affect results.

Several factors contribute to the lack of similarity of high-explosive and nuclear explosions at an interface. In the chemical explosion at an air-water interface, the pressure information in the water is propagated at a speed equivalent to Mach 5 in air. Since the air shock reaches this velocity for a very-short distance (if at all), it is readily seen that the water interface will accommodate itself to the impulse and, indeed, flow can be initiated in the direction and ahead of the advancing air shock during its passage. In the case of the nuclear explosions, however, the air shock is above Mach 5 for much of its passage over the central region, whereas the water shock is essentially sonic. It is difficult to see how flow toward the edge of the air shock can be significant under these circumstances.

An additional point of dissimilarity is the great radiant flux present in the nuclear explosion. From this it is not unreasonable to expect that a surface nuclear shot can, by radiant transfer, volatilize the water at some depth beneath. This suddenly volatilized water mass can then "explode." From this consideration one could expect that the nuclear inefficiency observed for land craters well might be quite unlike the case of water craters over deep water.

The mechanism of crater formation in general is intimately related to the direct generation of water waves. The only examples of wave generation involving the release of energies of the magnitude of the instant tests are the Mike shot of Operation Ivy and various volcanic and tectonic occurrences. It is also probable that submarine landslides and meteoritic falls have generated large waves. These generating mechanisms are not well understood. Shot Mike was extremely puzzling in its effects. No measurable wave was produced in the lagoon at a distance of 4 miles. At about 12 miles a wave of about 1½-foot amplitude was observed, and at 28 miles a wave of 3-foot amplitude occurred. Yet these waves arrived as though they had been generated close to zero point and traveled at the velocity of shallow water waves across the lagoon. This was a most astonishing result and can be explained only by the assumption that thermonuclear explosions are quite unlike other explosions in their wave-making characteristics or that the region of direct wave generation is excluded to the central region of the explosions, essentially to the region of crater formation. This region in the case of Shot Mike was completely occupied by the coral reef, and there occurred only a small amount of breaching of the crater into the lagoon. It must also be assumed that any wave component that increases with distance is obscured by the direct wave under ordinary test geometries. The possibility that this Mike wave was generated by the close-in fallout of debris on the water surface and that the near station was at a nodal point is discussed.

1.2.3 Wave Termination. A volume of experimentation exists on the forces and changes engendered by waves impinging on foreshores and various shore installations, but a rational understanding of the event of finite amplitude waves inundating a complex shore line can be only qualitatively described at present.

1.2.4 Summary. To summarize: The laws of the "trajectory" are well known, but the "primary and terminal ballistics" of water waves are not well understood.

Chapter 2
PROCEDURE

2.1 INSTRUMENTATION

Recorders used by the project for the measurement of wave height consisted of underwater pressure-time recorders. These were of seven types:

1. Floating stations. These utilized simple pneumatic pressure-time circular-chart recorders. The recorders communicated to the bottom through rubber-fabric hoses to bladders submerged 40 to 70 feet. These were located on coral heads in the lagoon at distances of several miles from the reefs. Each floating station was housed in a skiff and consisted of one clock-started and one continuous recorder. Pressure was referred to vacuum.
2. Mark IX shore recorders. These utilized a bourdon-potentiometer element on the bottom, cable-connected to a chart recorder ashore. These were initiated by hard-wire timing circuits. The pressure was referred to a long-period mean pressure having about 10 percent decay over a 10-minute period, except for the instruments employed for Shot 1, where the decay period was shorter.
3. Mark VIII shore recorder. The Mark VIII consisted of an underwater axial strain gage, cable-connected to a recording potentiometer ashore. Recording was initiated by hard-wire signals. Pressure was referred to vacuum.
4. "Turtle." This device, a submerged recorder, consisted of a pressure-resistant shell containing a direct-recording bourdon movement scribing a circular chart. This instrument was started by a surface-mounted thermal link. Pressure was referred to an enclosed, fixed air volume. This instrument allowed a close approach to the detonation.
5. Portable tsunami recorders. These were water-level recorders suitable for distant island stations. They utilized a hydraulic system that communicated with the water outside the reef by means of a hose and recorded via a float and potentiometer linkage on a strip recorder. The system included a band-pass filter, which reduced the tide range and reduced the effect of normal sea and swell. (Results reported in Reference 8.)
6. Tsunami recorders. Permanent installations, of the above nature, utilized strain gages and an atmosphere balance. These were installed in the United States. (Results reported in Reference 8.)
7. A deep-water ship-borne recorder. This consisted of a "vibration" absolute pressure transducer. The instrument was temporarily lowered from the ship to the bottom in deep water off the continental shelf of California. (Results reported in Reference 8.)

In addition, inundation (beer-can) gages were installed on many islands. Free-peak-pressure instruments carried by a free vehicle were used. Wave-measurement cameras were installed for Shots 5 and 6. Three "dunked" activity meters were constructed and used, and a number of instruments were constructed for use in a crash survey program on oceanic fallout. Underwater electrical potentials (UEP) were recorded from shipboard for three shots.

2.2 OPERATIONS

All stations were put in readiness prior to Shot 1. In Bikini Lagoon, this was accomplished by use of an especially equipped LCM, the project buoy boat, and the extensive use of self-contained diving apparatus. Timing and adjustments were set on minus-one or minus-two day depending on the conditions of the shot. In addition, the floating recorders were revisited on each 24-hour delay and were reset. Stations on distant islands were installed by the use of local craft of various types and self-contained diving apparatus. These stations were alerted by radio message where this was practical, but were, in general, in a condition of continuous recording.

The participation of the various lagoon instrument stations is tabulated by shots in Table 2.1.

Recovery of the records was effected with LCM, buoy boat, and helicopter and was accomplished by plus two days, except in the case of Shot 1.

Records were partially analyzed in the field in order to evaluate the wave heights and periods obtained. In addition, inundation lines were sketched from a helicopter and elevations were run to obtain indications of the height reached by the water in a number of places for Shots 2 and 4.

TABLE 2.1 INSTRUMENT PARTICIPATION

Station	Coordinates		Instrument		Shot Participation				
			Name	Type					
	North	East			1	2	3	4	5
163.01	152,200	112,600	Floating	*	†	‡	‡	‡	‡
163.02	152,650	136,100	Floating	*	§	¶	¶	—	—
					†	†	†	—	—
			Turtle	*	—	—	—	¶	¶
					—	—	—	†	†
163.03	144,200	157,600	Floating	*	¶	¶	¶	†	‡
					†	†	†	—	—
163.04	129,900	166,800	Floating	*	¶	¶	¶	¶	§
					†	†	†	†	†
163.05	115,500	176,400	Floating	*	‡	‡	‡	¶	¶
					—	—	—	†	†
162.01	109,800	179,000	Mark IX	*	¶	¶	¶	†	§
					†	†	†	—	†
			Mark IX	**	—	—	—	—	¶
					—	—	—	—	†
162.02	101,200	109,200	Mark VIII	*	†	¶	‡	‡	‡
					—	†	—	—	—
162.03	146,100	170,300	Mark IX	*	‡	†	¶	¶	‡
					—	—	†	†	—
162.04S	104,600	177,700	Mark VIII	*	‡	‡	‡	¶	§
					—	—	—	†	†
162.04D	103,600	179,300	Mark VIII	*	—	—	¶	—	—
					—	—	†	—	—
164.01	94,000	115,000	Free Inst	††	—	—	¶	—	—
					—	—	†	—	—

* Underwater pressure versus time.
† Occupied.
‡ Unoccupied.
§ Partially successful.
¶ Successful.
** Air pressure versus time.
†† Underwater peak pressure.

For Shot 3, inundation indicators were established on Sifo Island, Ailinginae Atoll, for visual observation from offshore.

Many estimates of wave heights were made during the progress of the tests for guidance of various projects and activities in an effort to minimize wave damage to installations. Other operations not directly related to the primary objectives of the project included underwater electrical potential, distribution of radioactivity in the lagoon, oceanic fallout surveys, lagoon-bottom conditions, and crater and other sonic surveys.

Chapter 3
RESULTS

3.1 RECORDED CHARACTERISTICS

In contradistinction to the Mike shot of Operation Ivy, all shots of the Castle series, except Shot 3 resulted in waves and disturbances that emanated from the central region (less than 2 miles in radius) of the explosion and were recorded at the various lagoon stations of the project. Data on the recorded crests and troughs is presented in Table 3.1. A plot of first-crest arrival times versus range is given in Figure 3.1. Wave heights as a function of time at various ranges are reproduced in Appendix B. In addition, waves were recorded at distant stations located outside the lagoon. The records obtained at the distant stations have been published in reports (Reference 8) dealing exclusively with open-ocean long-period seismic-type sea waves from shots of Operations Castle and Redwing.

In general, several different phenomena were recorded by each of the lagoon instruments for each shot.

The first phenomenon was a short-period highly damped series of ground or water-transmitted shocks. The time resolution of the instrumentation was inadequate to resolve the individual arrivals. However, they do not correspond to any readily explicable mode of oscillation of the instrument system and seem to possess a period of 6 to 7 seconds. They possibly represent a series of arrivals of compression waves roughly corresponding to a lateral passage of a shock wave through the atoll.

Following this damped series, the record is marked with the arrival of the air-transmitted shock wave. The floating recorders were so disturbed by this arrival that the record becomes incoherent and the following 60 to 90 seconds of record are lost. The shore and "turtle" recorders, however, display a typical sharp-fronted shock wave followed by a rarefaction.

The air-pressure instrumentation, Station 162.01, Shot 5, recorded the air shock in some detail. The record displays a complexity to the rarefaction phase, which is discussed below.

Lastly, for Shots 1, 2, 4, and 5 the farther stations recorded a gentle seiche-like oscillation of about 3 to 6 inches of water pressure with periods of from 2 to 4 minutes. These fluctuations appear on several types of recorders and undoubtedly indicate real pressure changes. They cannot be correlated at the various stations. These could have resulted from barometric, water-surface, or ground fluctuations. If they were simple water-level fluctuations, they arrived at a time that taxes one's imagination regarding their origination and propagation from the central region. They could have been generated secondarily at a distance by the air shock, water-ground shock, or afterwinds. In an effort to ascertain if they were barometric fluctuations, a pressure transducer of the Mark IX type was set to record the air wave at Site Nan, Station 162.01. The interpretation of this record is not clear. The record was complex for a period of time after the passage of the air shock. Periods of atmospheric-pressure change that would correlate with those observed in the water wave traces were not apparent. However, there is little correlation between these phenomena of any shot.

These early, low-amplitude pressure changes cannot be related to any simple seiching motion of the lagoon. No evidence of seiching can be observed in any record prior to arrival of the air shock, and the observed changes in pressure usually commence immediately following the passage of the overpressure. Hence, they would appear to be generated by the air shock. These early pressure fluctuations appear more consistently in records at stations close to islands than at central lagoon stations, and a possibility exists that these may result from island interference with the air pressure wave. The air pressure wave may possibly receive some reinforcement

TABLE 3.1 TABULATED DATA

Surface water waves in 60 feet of water; heights above mean tide stage.

Station Number	Air-Line Range	Estimated Lagoon Path Range	First Crest Height	First Crest Duration	First Trough Depth	First Trough Duration	Max Crest Height	Time Lapse Between First Crest and Max Crest or Crests	Max Trough Depth	Time Lapse Between First Crest and Max Trough or Troughs	Arrival Time After First Crest	Long Period Trough Duration
	naut mi	naut mi	ft	sec	ft	sec	ft	min	ft	min	min	min
Shot No. 1												
162.01	19.8	20.1	1.1 *	162	4.3 *	234	2.2 *	5.8	First Trough	3.8	—	—
							2.2 *	27.9				
163.04	16.6	17.3	1.4	132	0.8 †	—	1.5	18.5	2.2	10	2	14
163.03	14.2	14.8	1.3	108	1.0	108	First Crest	—	First Trough	2.2	1.1	19.9
									1.0	5.3		
Shot No. 2												
162.01	19.8	20.1	1.9 *	138	6.4 *	252 *	3.6 *	5.9	First Trough	4.2 *	—	—
163.04	16.6	17.3	2.5	120	0.9 †	—	First Crest	—	2.1	9.4	1.1	12 †
163.03	14.2	14.8	1.6	126	0.7 †	—	1.7	27.6	0.9 ‡	5.1	1.2	7.8
162.02	13.0	13.0	2.9 *	84	2.6 *	150 * †	First Crest	—	First Trough	1.0 *	—	—
163.02	10.3	10.9	2.2	168	—	—	First Crest	—	1.3 ‡	4.2	1.0	6.9
Shot No. 4												
162.04 S	14.0	14.1	3.4 *	72 *	1.3 *	24 *	9.7 *	2.4	—	—	—	—
163.05	12.4	12.5	5.2	90	2.6	72	First Crest	—	4.4 *	6.9	—	—
163.04	9.7	9.8	5.2	90	2.4	84	First Crest	—	3.2	2.3	—	—
162.03	9.2	9.6	5.0 *	90	0.5 *	24	First Crest	—	5.7 *	7.6 *	2.9	8.3
163.02	3.5	3.5	14.0 §	42	8.8	63 *	First Crest	—	First Trough	1.0	—	—
			13.3 ¶									
Shot No. 5												
162.04 S	14.0	14.1	7.0 *	—	—	—	—	—	—	—	—	—
163.05	12.4	12.5	7.9	66	3.5	120	First Crest	—	6.3	6.9	—	—
			28 §									
163.02	3.5	3.5	25.3 ¶	72	—	—	First Crest	—	10.3	9.4	—	—

* Reflection component included.
† Waves of significant period and amplitude superimposed, interference significant. Estimated value if interference had not been present.
‡ Maximum long period trough depth. Trough symmetrical about this value.
§ Measured from mean tide stage.
¶ Measured from leading water level change.

as it receives displacement in passing over the islands. This might result in an additional pressure pulse or the origin of a small reflected pressure wave, which could reach the pressure transducers adjacent to the island.

If these observed pressure changes are wave-like motions of the lagoon bottom, similar to the "Grandpa" wave observed in seismic work, (an interfacial wave observed between an ordinary muddy bottom and water, with a propagation velocity greater than a gravity wave but less than an elastic wave) they must possess a propagation velocity of the same order as the air shock

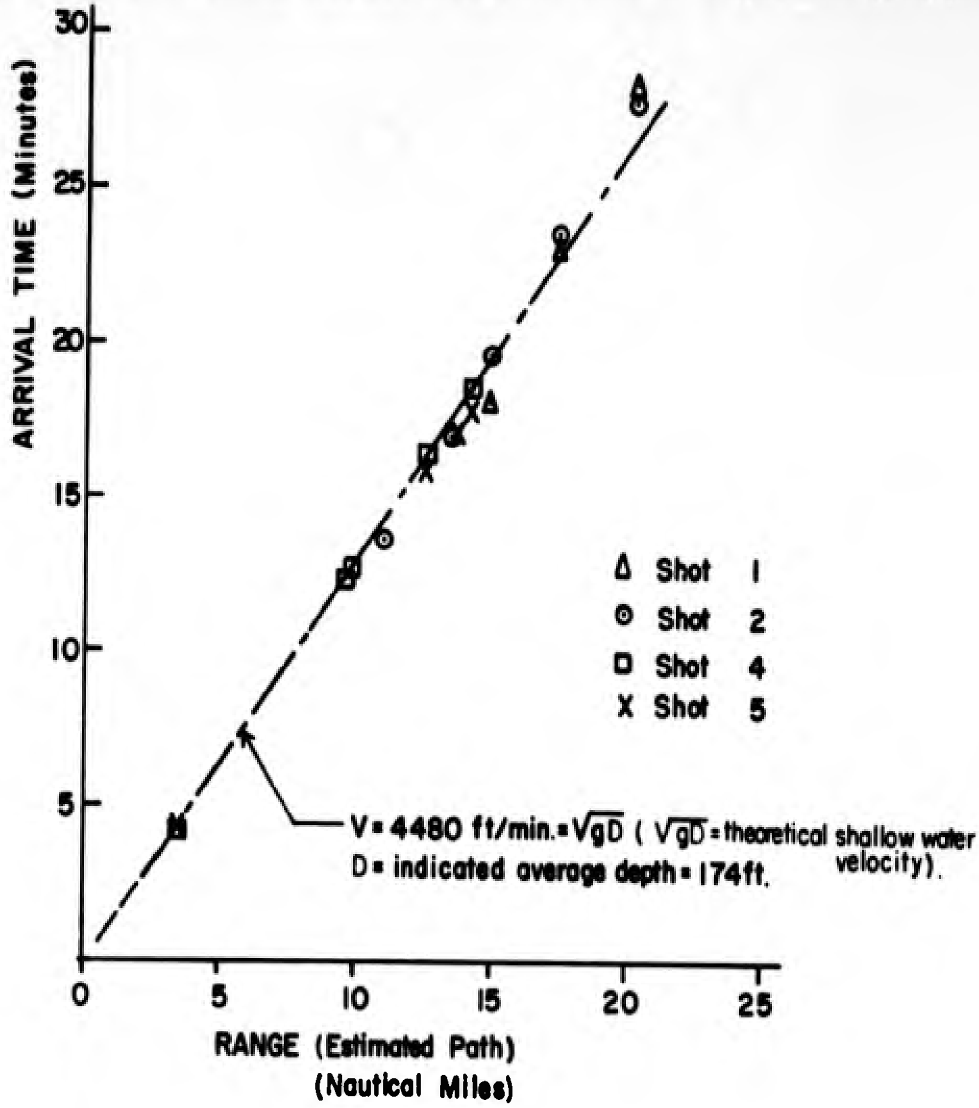


Figure 3.1 First-crest velocity.

(approximately 1,000 ft/sec). Equilibration of the lagoon water surface could not take place as the propagation velocity of such a wave would be much higher than that of a "free" water-surface wave.

Under these circumstances, the pressure effect would result from the acceleration of the overlaying water. If this is the case, the deeper instruments should display a higher signal, since the mass of water accelerated is greater. This was not observed, however. We have estimated that a 4-inch pressure fluctuation over a 4-minute period in 70 feet of water from this mechanism would require a change of bottom position of about 200 feet. Since such vertical excursions certainly did not occur, we must eliminate accelerative forces as an explanation.

These advance pressure fluctuations interpreted as wave action are similar to those first observed and reported in Reference 9. In this experimental work with high explosives, these advance waves (recorded as surface water elevation and not subsurface pressure changes) appeared to be associated with unique conditions at the origin, such as water depth, bottom hardness, and generative conditions affecting the directly generated wave system wave lengths. The scaled water depths in which this phenomenon was observed were much greater than the water depths involved in the Bikini Lagoon tests. For the water depths in which this was experimentally observed, the range at which these induced waves were observed was inversely proportional to the water depth.

Certainly these are interesting occurrences and represent very-early events in the time scale of the travel of water waves.

In the case of the close-in instruments, the "turtles," the passage of the air shock and rarefaction is succeeded by a rather abrupt rise of approximately 1.0 to 2.5 feet in water pressure, which then slowly increases for about 3 minutes or until the first large crest arrives. Since these instruments are roughly treated by the ground and water shock, the explanation of this conduct was sought in possible results of these disturbances. One suspected disturbance is that the instruments may be shaken down the sides of the coral knolls to greater depth. However, the record returns to the original zero line during the following hour, which eliminates this possibility. Heating of the instrument case would have the opposite effect and would appear as an apparent pressure drop. Hence, this cannot be the cause. It appears that this pressure rise might result from large quantities of water and coral debris falling on the water surface. If this were so, it would require a layer of about 2 feet falling over an area at least as large in all directions about the instrument as the propagation distance of a free wave in the local water depth over a period of 3 minutes.

This free-wave velocity is about 4,000 ft/min (a function of water depth only). The instrument was 21,000 feet from surface zero. An approximation of the minimum quantity of material to accommodate this is a layer about the instrument that would result in a pressure increase of approximately 1 psi (2 feet water) over a radius of 12,000 feet. As the symmetry of fallout of debris suggests that the pressure rise must be symmetrical about surface zero, a washer-shaped area would have to exist that has an inner radius of 9,000 feet and outer radius of 33,000 feet about surface zero. A displacement of 2.0×10^{8} tons of water or debris would be involved. Considering that the material arises from an initial cylindrical crater 300 feet deep through 200 feet of water and 100 feet of sediment (an equivalent of 400 feet of water), this quantity is supplied by a cylinder about 2,000 feet in radius. Thus, this explanation may be reasonable from the standpoint of the material available, but we have not ascertained if this magnitude of close-in material deposit has been observed. Alternatively, the characteristics of these records are compatible with a fallout of water and debris of about 3 lb/in^2 at the crater edge grading to zero at 33,000 feet or with a heavier fallout at the crater edge grading to zero at a lesser distance.

The suspected water debris fallout at the turtle stations may constitute an explanation for the curious results from Shot Mike, Operation Ivy. If the wave from Mike resulted from debris thrown into the lagoon up to radii of 2 to 3 miles, the closest station may have been at a nodal point in the subsequent seiche-like movement. The resulting seiche-like motion of the entire lagoon would display a greater height at the extreme ranges than at the mid-points and also would appear to be propagating at the velocity of a free wave. The point is that the debris produces a relatively long period impulse on a large part of the lagoon surface and hence can give rise to seiching of adequate magnitude, whereas an impulsive event could produce equivalent shorter-period waves visible at the near stations. For Shot Mike, instruments sensitive to pressure changes on the order of ½ inch of water did not observe any close-in water-wave action.

These earlier events are lost abruptly in the arrival of the direct water wave. The first arrival in all cases was a crest followed by a trough, which was transected by secondary crests. For Shots 1 and 2, this first trough appeared at most stations as the beginning of a more-extensive trough with an equivalent wave length a minimum of three times as great as that of the first crest. The exceptions to this were the waves recorded by the near-shore and near-reef stations, where the extensive trough is not clearly observed. This large trough is absent from the records of Shots 4 and 5.

A second principal crest occurred at varying times after this prolonged trough. For Shots 1 and 2, this second principal crest occurs shortly after the trough passage, and for Shots 4 and 5

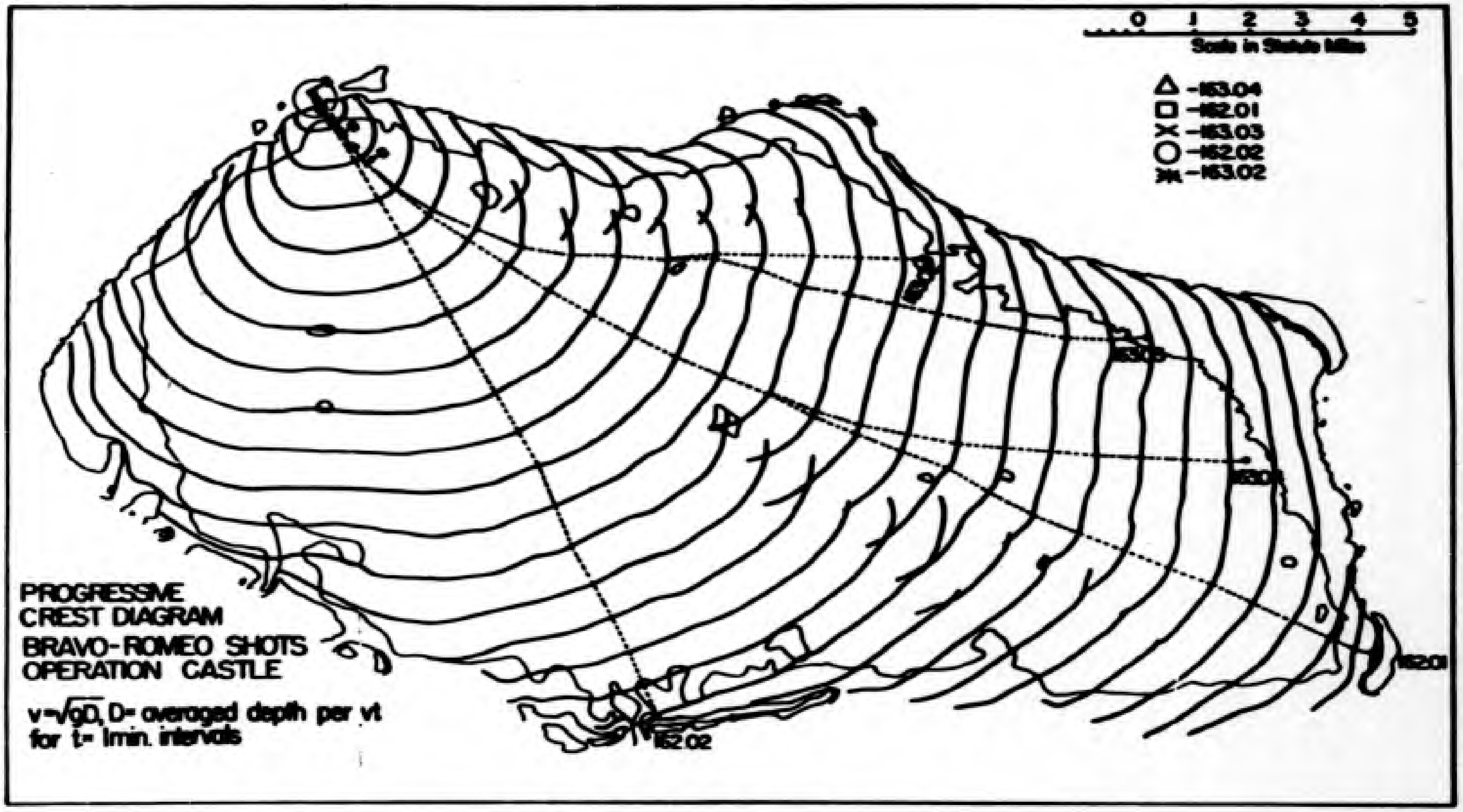


Figure 3.2 Progressive crest diagram, Shots 1 and 2. $v = \sqrt{gD}$, D = averaged depth per vt for t = 1 min intervals.

this crest occurs at proportionately later times at greater range from surface zero. At stations farther than one half wave length (½ mile) from the nearest reef or island the first crest was the highest, but at stations closer to shore, equally large or larger crests occurred elsewhere in the train, apparently resulting from reinforcement.

Shot Baker, of Operation Crossroads, and some high-explosive tests had generated wave trains in which the first wave consisted of a distinctly separate solitary wave followed by a train of oscillatory waves. The solitary wave retained its individuality over all distances and traveled somewhat faster than the following oscillatory set. The Castle data cannot be interpreted with regard to this individuality of the first wave. It is possible that reflected waves originating from islands and reefs close to ground zero obscure this previously observed and anticipated phenomenon. Reflections undoubtedly contribute to the nonsystematic wave traces measured at various stations for various shots.

3.2 WAVE VELOCITY

The discussion of wave heights and time at various ranges is restricted to first crests. The records are only generally similar at various ranges. All records become complicated by reflection, etc., within 4 minutes after the arrival of the first crest. A plot of first-crest arrival times versus range for the four principal shots is presented in Figure 3.1. Progressive crest (refraction) diagrams for the two principal shot locations are included as Figures 3.2 and 3.3. Wave-crest positions about ground zero are drawn from travel times based on $\sqrt{gD}$, where D is an average water depth over the time interval. Velocity corrections for finite wave height have been neglected since a comparative calculation of height effect upon propagation velocities at a radius of about 1 mile indicated these to be insignificant in this instance. Propagation velocities for these waves in shallow water are, of course, affected at all ranges. Effects of prominent central-lagoon coral heads are visible. Utilizing the measured first-crest arrival times for the indicated stations and projecting back to zero time over the estimated path to ground zero gives indicated radii of generation.

The more-direct wave paths (free from prominent refraction and farthest removed from the northern reef) result in less scatter of these indicated radii about ground zero. This effect is most noticeable in the data for Shots 1 and 2. The range of scatter of indicated radii of generation for Shots 4 and 5 is less than that of 1 and 2.

The scatter of data available precludes any conclusions about this calculated apparent radius of first-crest generation except to say, in a general way, that the first crest originated within 2 miles of zero point.

3.3 WAVE HEIGHT AS A FUNCTION OF RANGE

The data of wave height versus range is plotted in Figure 3.4. Dashed lines representing exponents of height decay with increasing range of 0.8 and 0.7 are given. The experimental data is from Table 3.4. Figure 3.4 indicates that $H \propto 1/R$ for Shots 4 and 5. The lack of data over sufficient ranges and the scatter of available data prevents any conclusions regarding H as a function of R for Shots 1 and 2.

3.4 SCALING CONSIDERATIONS

Characteristics of wave height versus time at various stations for the four Bikini Lagoon shots is presented in Table 3.1. A study of the original traces revealed that an interpretation of recorded values without consideration of the complexity of the reflection-refraction processes would be extremely misleading. Where permissible, an attempt has been made to note individual recorded wave features according to the degree of influence of the topography and geometry of the test site and station location. The effect of refraction on wave height superimposed on initial curvature is small in comparison with the disturbances of reflection and has not been entered into the

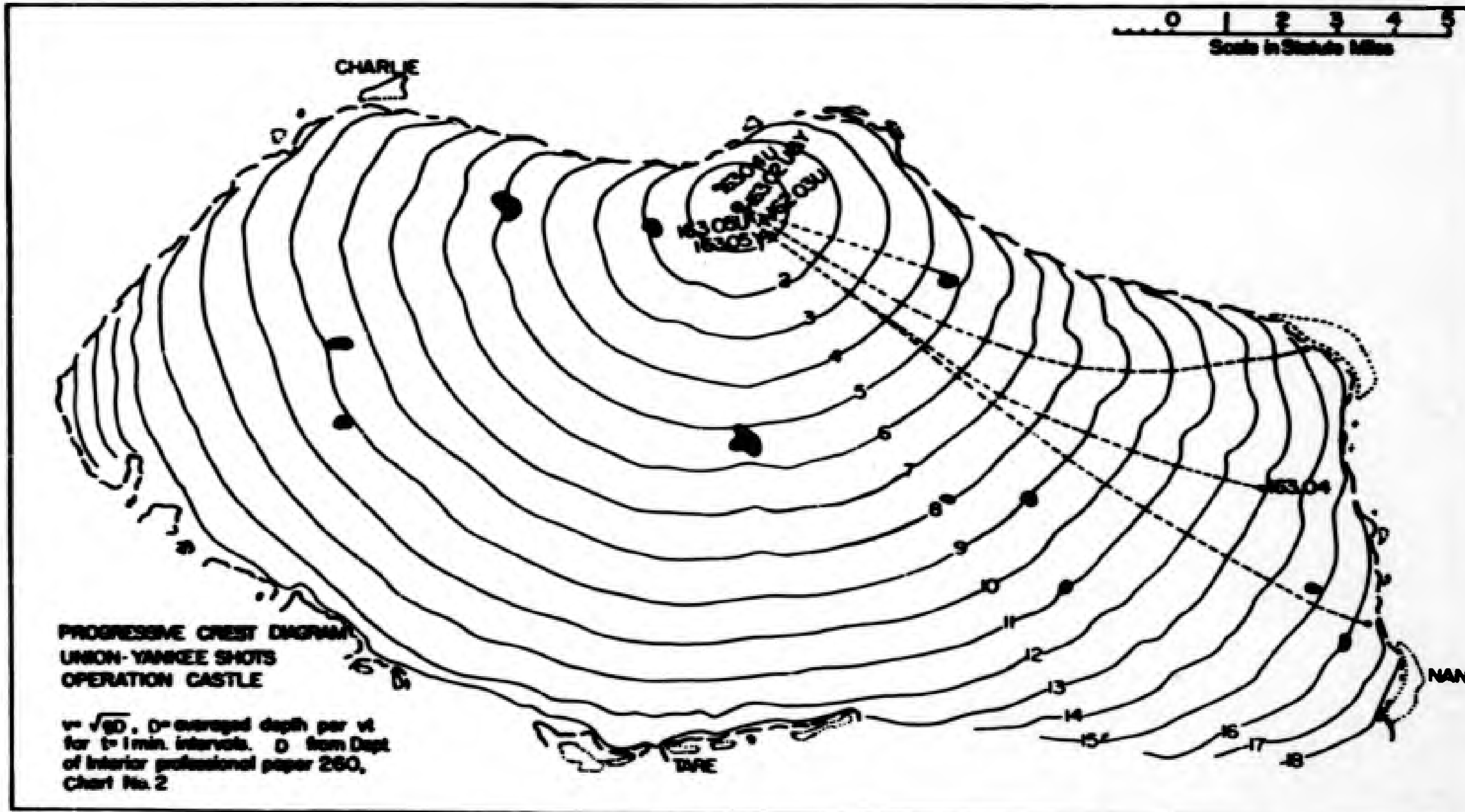


Figure 3.3 Progressive crest diagram, Shots 4 and 5. $v = \sqrt{gD}$, D = averaged depth per vt for t = 1 min intervals. D from Dept. of Interior professional paper 260, Chart No. 2.

results of wave height. An attempt to identify the sources and estimate the degree of influence of reflected waves by means of travel times from possible reflectors met with complete failure.

The recorded traces indicate the waves from Castle tests underwent extensive changes in period and amplitude when within approximately one half wave length of a land or reef area. In most cases, the first crests maintained their identity in period when close to land areas. The data does not support a similar statement about the first-crest height. Observed characteristic features of the wave system in the central lagoon were lost when these waves approached an island or reef, and the component waves assumed a new time-height history that appears to be more a function of surrounding topography than of the original features of the waves in the open lagoon.

Prior to the following analysis, an attempt was made to fit first-crest heights to a partially empirical equation involving weapon-yield scaling to the one half power. Terms were introduced in an attempt to account for the breeching effects of Shots 1 and 2. Green's Law was also included in these efforts to transfer wave heights to a common depth for comparison purposes.

It was hoped that for this final report, scaling considerations could be extended to include the complete wave system, but it now appears that the influence of Bikini Lagoon upon these waves was even more pronounced than first imagined and that scaling techniques and wave-system analysis involving more than the first crest are still beyond the scope of Castle data. Comparisons of experimental data with two- or three-dimensional mathematical treatments that might possibly be made to fit the conditions of generation are impossible at the present because of the various complexities described above.

Table 3.4 summarizes the fit of experimental data to a partially empirical equation. This equation in its simplest form

$$H_1 R_1^{\,m} = KW^n \qquad (3.1)$$

has evolved from repeated measurements and study of impulsively generated water waves. Experimental measurements have shown that for shallow-water wave systems the product of the first wave height times the range of observation is a constant (Reference 10). Also, for waves generated and propagating in deep water, the product of the highest wave in the group and the range of observation has experimentally been shown to be a constant (Reference 9).

If the percentage of charge energy radiating as water waves is assumed constant for various yields and the wave shape of the first wave is assumed sinusoidal, a theoretical equation for shallow-water waves can be derived (Reference 10). The exponents $n = \frac{1}{2}$ and $m = 1$, and H, the wave height, apply for the first wave only over the ranges in which the majority of wave energy is in the first wave. Equation 3.1 with $n = \frac{1}{2}$, $m = 1$ can also be developed theoretically for wave systems from explosions in deep water if all linear dimensions are assumed proportional to bubble radius (Reference 9). In this latter case, H is the maximum wave height in a group of waves.

Results of Shot Baker, Operation Crossroads, tended to show that H was proportional to $W^{1/4}$ and R was proportional to $W^{1/3}$ where the depth of water varied as the cube root of charge weight. The value for H was given as the highest wave in this data. This information indicated that the HR product was increasing more rapidly with increasing charge weight ($W^{7/12}$) than the $W^{1/2}$ indicated by model law considerations alone. Crossroads Baker also showed that the wave system was composed of two related but distinct parts: the first wave and a following group of waves. For the first 8,000 feet of travel, the first wave was significantly higher than all others, but beyond this range the highest wave tended to be found farther and farther back in the wave system. In other words, the first wave was decreasing in height with range at one rate, and the highest wave in the following group was decreasing at another and slower rate. When examining a given wave system to find a maximum wave height, the range of the wave system from the origin determines in which part the highest wave will be found. The distance from surface zero at which the highest wave moves to the following group is probably scalable with charge size. The data of Reference 12 indicates that the model law of Reference 10, which showed the proportionalities of R and H to W above, where H is the highest wave, is also applicable to the first wave height (H_1) out to ranges of approximately 12,000 feet. This is also indicated by comparing the relative magnitudes of the highest wave to the next highest wave for ranges less than, and greater than, 8,000 feet; considering the limitations of experimental errors (± 30 percent for data of Reference 11), it is observed that the first crest height is the predominant dimension affecting the curve slope from which the H, R, and W proportionalities were derived. It is apparent that the model

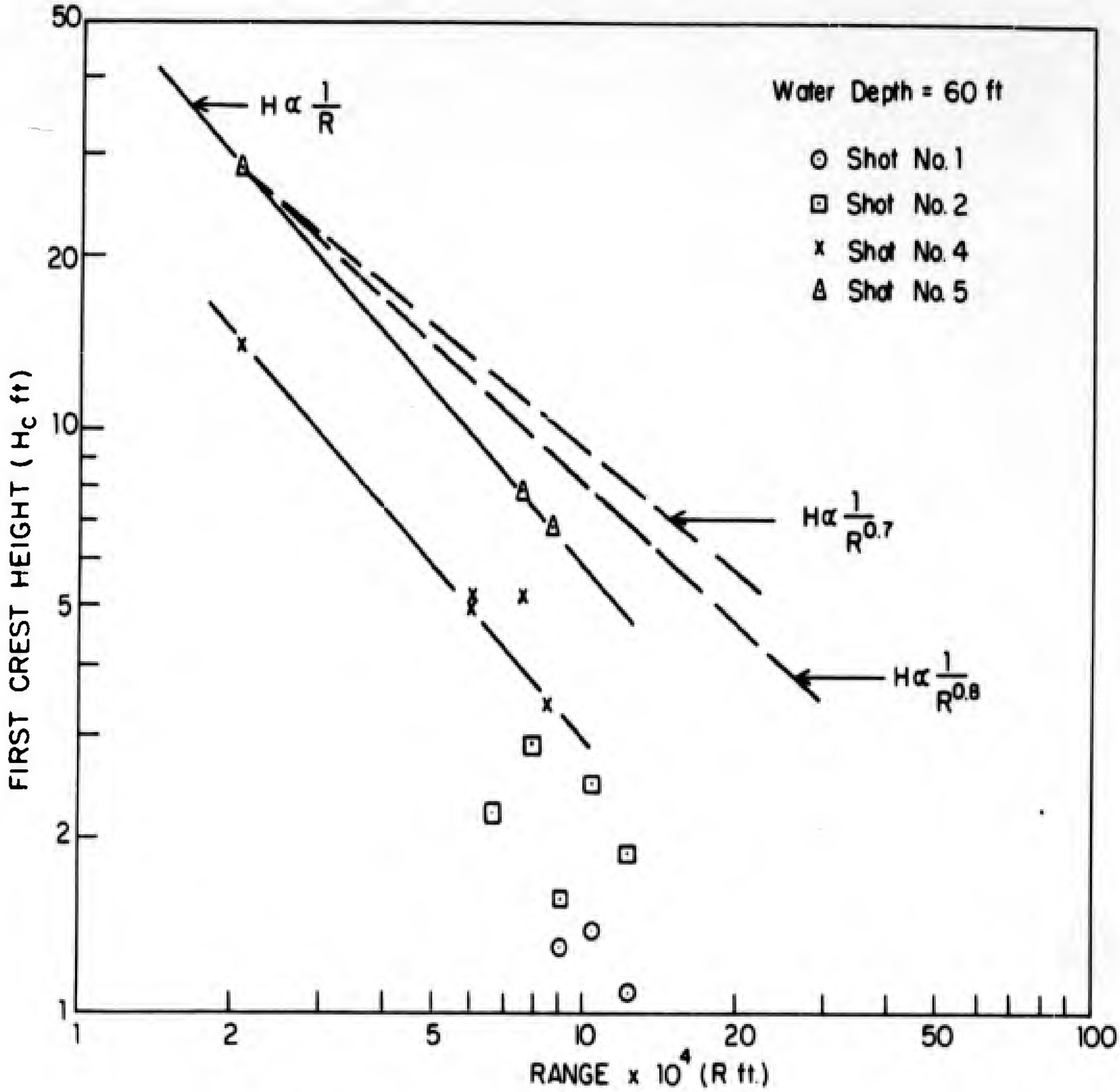
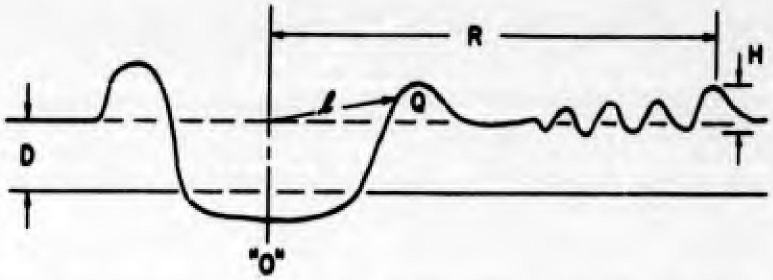


Figure 3.4 First-crest height versus range.

law resulting from the Baker test is equally applicable to the first wave heights (H_1) for scaled ranges less than $R/W^{1/3} \leq 35$.

The results of Reference 11 give scaling equations in which $0.7 \leq m \leq 0.8$ and $0.48 \leq n \leq 0.52$. It was apparent from a comparison of the recorded wave heights for Shots 4 and 5 when either $W^{1/2}$ or $W^{7/12}$ scaling was used, that the increased depth of water in the region of wave generation for Shot 5 increased the generated wave height. Examination of the Castle wave data is required to determine the relationship of water depth, wave height, and range of observation as a function of yield. To compare the wave data for the various geometries of detonation of the Castle series, it is necessary to consider variables of generation affecting wave height that normally are minimized or eliminated in other tests.

A model of these wave-generation variables is discussed. This model is intended to apply only for yields and water depths where $l \gg D$ and the floor of the lagoon is exposed by the water crater over a significant area.



The following assumptions are made: (1) The energy coupling for the generation of waves is unaffected by water depth as long as $l \gg D$. (2) The generated waves result from water which is moved outward by the initial impulse, and the quantity of water involved, Q, is limited only by the depth D and the radial distance, (l), at which the first wave breaks away from the crater cavity. (3) The energy in the water mass, Q, is in the form of potential and kinetic energy, and the division of total energy accountable to these two forms is an indeterminate ratio and related to the parameters of generation W and D for $l \gg D$. (4) The potential and kinetic energy in the first wave at the breakaway point (l) is equal to the energy of the wave system at $R \gg l$.

Two alternatives considered are (1) the generation phenomenon is related principally to shock motion and (2) the phenomenon is related principally to nonshock motion.

l = some dimension of the water crater where wave breakaway occurs.
Q = the quantity of water, limited by depth D and l.
D = depth of water.
R = radial distance to a formed wave system at a point of observation where $R \gg l$.
T = typical time.

From Assumption 1, the geometric model laws apply,

$$l \sim W^{1/3} \qquad (3.5)$$

$$R \sim W^{1/3} \qquad (3.6)$$

$$T \sim W^{1/4} \quad \text{Alternate (1)} \qquad (3.7)$$

$$T \sim W^{1/3} \quad \text{Alternate (2)} \qquad (3.8)$$

Then $$Q \sim l^2 D \sim W^{2/3} D \qquad (3.9)$$

The velocity at breakaway,

$$V \sim \Delta l / \Delta T \qquad (3.10)$$

$$V \sim W^{1/12} \quad \text{Alternate (1)} \qquad (3.11)$$

$$V = \text{Constant} \quad \text{Alternate (2)} \qquad (3.12)$$

The kinetic energy of the water,

$$E_k \sim QV^2 \qquad (3.13)$$

$$E_k \sim K_1 W^{5/6} D \quad \text{Alternate (1)} \qquad (3.14)$$

$$E_k \sim K_2 W^{2/3} D \quad \text{Alternate (2)} \qquad (3.15)$$

The potential energy of the water, Q

$$E_p \sim l^2 D^2 \sim K_3 W^{2/3} D^2 \qquad (3.16)$$

From Assumption 3, the total energy in the wave at Q is

$$E_p + E_k \sim K_3 W^{2/3} D^2 + K_1 W^{5/6} D \quad \text{Alternate (1)} \qquad (3.17)$$

$$E_p + E_k \sim K_3 W^{2/3} D^2 + K_2 W^{2/3} D \quad \text{Alternate (2)} \qquad (3.18)$$

If the wave forms in the system at R are assumed sinusoidal, the energy in the significant waves at a distance from the origin are

$$E \sim \Sigma_1^N H_n^2 R_n \lambda_n \sim N(H_a^2 R_a \lambda_a) \qquad (3.19)$$

Where: N = number of significant waves
H_a = an average wave height in the system
R_a = an average range of waves in the system
λ_a = an average wave length
$(H_a^2 R \lambda_a)$ = a single wave containing $\frac{1}{N}$ the total energy of the wave system.

Assuming that the first wave is an average wave,

$$E_1 \sim H_1^2 R_1 \lambda_1 = \frac{1}{N}(E_p + E_k),\ R_1 >> l, \text{ Assumption 4} \qquad (3.20)$$

$$\lambda_1 \sim W^{1/3} \text{ (Shallow water) Reference 9} \qquad (3.21)$$

$$\lambda_1 \sim R_1 \text{ Reference 10 and Reference 9 when } R \sim W^{1/3} \qquad (3.22)$$

$$H_1 \sim W^{1/4} \text{ Reference 11} \qquad (3.23)$$

$$H_1 \sim D^{2/3} \text{ Reference 11} \qquad (3.24)$$

$$D \sim W^{3/8} \qquad (3.25)$$

The energy of the water Q, with $D \sim W^{3/8}$

$$E_p + E_k \sim K_6 W^{34/24} + K_4 W^{27/24} \quad \text{Alternate (1)} \qquad (3.26)$$

$$E_p + E_k \sim K_6 W^{34/24} + K_5 W^{25/24} \quad \text{Alternate (2)} \qquad (3.27)$$

If the ratio $E_p/E_k = f(W^{1/6}/D)$ over the ranges of 7 Mt to 15 Mt, i.e., $K_4 = K_5 = K_6$ is approximated by

$$E_p + E_k \sim W^{1.63} \quad \text{Alternate (1)} \qquad (3.28)$$

$$E_p + E_k \sim W^{1.58} \quad \text{Alternate (2)} \qquad (3.29)$$

From Equation 3.20, the energy in the first wave

$$H_1^2 R_1 \lambda_1 \sim \frac{1}{N} W^{1.63} \quad \text{Alternate (1)} \qquad (3.30)$$

$$H_1^2 R_1 \lambda_1 \sim \frac{1}{N} W^{1.58} \quad \text{Alternate (2)} \qquad (3.31)$$

From Equation 3.22

$$H_1^2 R_1^2 \sim \frac{W^{1.63}}{N} \quad \text{Alternate (1)} \qquad (3.32)$$

$$H_1^2 R_1^2 \sim \frac{W^{1.58}}{N} \quad \text{Alternate (2)} \qquad (3.33)$$

The number of waves in a system at a range well removed from the zone of generation has been examined by Reference 9. This study was of waves generated in deep water. For large charges in deep water, the number of waves at geometrically similar ranges was found to vary as the charge weight to the $\frac{1}{12}$ power. For conditions of generation approaching those of the Castle tests, the data of Reference 9 indicated the relationship between N and W changed. The ratio of crater dimensions to water depth for the Castle tests are radically different from the range of Reference 9 data. Crossroads data (Reference 10) shows that the number of waves, excluding the first, increases linearly in direct proportion to time or range. The Castle data does not permit conclusions about the variation of the number of waves as a function of time, range, or yield and it is necessary to assume that

$$N \sim R \sim W^{1/3} \quad \text{(Equation 3.6)} \quad l >> D \tag{3.34}$$

It is also noted that if Alternate 1 is the accepted scaling, the number of waves could be considered proportional to charge size to the $\frac{1}{4}$ power.

Equations 3.32 and 3.33 become

$$H_1R_1 \sim W^{0.65} \quad \text{, Alternate (1)} \tag{3.35}$$

$$H_1R_1 \sim W^{0.62} \quad \cdot \text{ Alternate (2)} \tag{3.36}$$

$$l >> D \text{ i.e., } 7 \text{ Mt} \le W \le 15 \text{ Mt}$$

$$H \sim D^{2/3}$$

Comparing Equations 3.35 and 3.36 with experimental results of Crossroads Baker and related tests and with other scaling equations derived from theoretical model considerations alone, the indicated first wave size with range scaling for charge size is slightly greater than $W^{1/2}$ and $W^{7/12}$.

For Castle Shots 1 and 2, where the device energy that can appear in the form of directly generated water waves is a function of the crater breach angle to the lagoon, a factor to account for this variable is inserted in Equations 3.35 and 3.36. We assume that diffraction is complete at $R >> l$. The first wave height at R is a function of the quantity of escaping energy through some angle of breach at the crater.

$$E_p + E_k \sim \frac{\phi}{\pi} \tag{3.37}$$

$$H_1^2R_1^2 \sim f\left(\frac{1}{N}, \frac{\phi}{\pi}\right) \tag{3.38}$$

If we assume that the reduction in wave system energy due to crater breach effect appears in the first wave height at all ranges including $R >>> l$,

$$H_1R_1 \sim \left(\frac{\phi}{\pi}\right)^{1/2} \tag{3.39}$$

The effect upon the wave height of material density in the region of crater formation cannot be approximated by any simple reasoning. It is suggested that the water, in the case of Shots 1 and 2, attains its energy from the horizontal introduction of an intermediate material. The density of this intermediary can logically be assumed to reduce the energy received by the water and is inversely proportional to wave energy. The factor $1/\rho^{1/2}$ is entered in the general equation to approximate this effect and to attain dimensional homogeneity.

The form of Equations 3.35 and 3.36 with additions to account for breaching and crater density is

$$H_1R_1 = KW^n\left(\frac{\phi}{\pi\rho}\right)^{1/2}, \quad 0.5 \le n \le 0.65, \quad H \sim D^{2/3} \tag{3.40}$$

For the range of yields involved in the Castle tests, it is desirable to see if the data available will give any indication of the most applicable exponent of W. Because of the difficulty in assigning depth of water values for Shots 1 and 2, the depth effect is excluded in the Castle yield-range comparison. The wave height values H_C, breach factors, and density factors used are those given in Table 3.4. The range values used are the paths of travel shown in the refraction diagrams and in Tables 3.2a and 3.2b. First crest dimensions (H_C) are used in these considerations instead of first crest to following trough dimensions (H_1) because the wave traces show considerable nonsystematic variation as a function of range for first trough depths. The influence of Bikini Lagoon upon radiating waves following the first crest appears to be more pronounced than upon the first crest alone.

$$H_C = H_1/2. \quad \text{assumed} \tag{3.41}$$

The variations of K in Equation 3.40 for $n = 1/2$ and $n = 7/12$ are as below.

Shot	Average K, $n = 1/2$	Average K, $n = 7/12$
1	0.96	0.76
2	1.08	0.88
4	1.20	1.02
5	1.63	1.31
Departure of Extremes	34 percent	32 percent

The test data alone does not permit conclusions about the exponent of charge weight. The effect of increased water depth of generation of Shot 5 with respect to Shot 4 in the above comparison is apparent. The close agreement of K values for Shots 1 and 2 (for a given exponent n) tends to indicate that the crater density factor as entered in Equation 3.40 is adequate because the crater breach angle observed after Shot 1 was not significantly increased by Shot 2.

The results of the Crossroads Baker experiment showed that

$$H_1R_1 = 4.2\ W^{7/12} \quad \text{Reference 10 where} \tag{3.42}$$

$$D/W^{1/3} = 0.5 \tag{3.43}$$

The water depth in the zone of wave generation for Crossroads Baker was approximately 170 feet, while that of Castle Shot 4 was approximately 160 feet. The difference between these two depths is equal to the variation of the water depth about 360 degrees of circumference, so the depths of generation for the two tests are considered the same. The data of Reference 11 indicates that for yield and water depth combinations where a prominent bottom crater is formed, the depth of zero point below the water surface has a minor effect upon wave heights. For purposes of comparing Crossroads Baker data with Castle Shot 4, the depth of submergence is considered a negligible factor.

Scaling up from Crossroads Baker data to Castle Shot 4 yield gives

$$H_1R_1 = 4.2\ W^{7/12} = 34.8 \times 10^5\ \text{ft}^2 \tag{3.44}$$

$$H_1R_1 = 18\ W^{1/2} = 21.3 \times 10^5\ \text{ft}^2 \tag{3.45}$$

$$\text{for } W = 7\ \text{Mt}, \quad D/W^{1/3} = 0.50, \quad R/W^{1/3} \le 35.$$

Water waves from both tests were measured in the open lagoon waters in an assortment of water depths. Castle wave heights were transferred to a common water depth of 60 feet for purposes of study and comparison. These are the heights given in Table 3.4. The average height-range product of Shot 4 waves in 60 feet of water is

$$H_C R = 3.17 \times 10^5\ \text{ft}^2 \tag{3.46}$$

To minimize uncertainties that might arise from questions about the validity of the technique of transferring waves from their recorded depth to the 60-foot standard depth, the product (Equation 3.46) is adjusted to a water depth that more nearly agrees with the depth at which the majority of waves were recorded. This depth is 160 feet (the average depth of generation), and the transfer is accomplished in the reverse manner of that described in Appendix A.

$$H_C R_1 = 2.48 \times 10^5\,\text{ft}^2 \qquad \text{(Shot 4 waves in 160-foot water)} \tag{3.47}$$

$$H_C = H_1/2$$

$$H_1 R_1 = 4.96 \times 10^5\,\text{ft}^2 \tag{3.48}$$

$$\text{for 7 Mt and } D/W^{1/3} = 0.064$$

The data from Shots 4 and 5 and from Reference 11 has indicated that wave size is sensitive to water depth in the zone of generation. The scaled water depths of the two tests being considered, Crossroads Baker and Castle 4, are $D/W^{1/3} = 0.5$ and $D/W^{1/3} = 0.064$. The high-explosive data of Reference 11 indicates that for a reduced distance of $R/W^{1/3} = 10$, the wave height varies as $D^{0.7}$, the water depth of generation. For Crossroads Baker and Castle 4, this scaled range is 3,420 feet and 24,000 feet respectively, which is sufficiently close, less than $R/W^{1/3} = 35$, to zero point that the first wave scaling of Reference 10 is applicable. The range of $D/W^{1/3}$ of Reference 11 for which $H_1 \propto D^{0.7}$ was found applicable was $0.08 \leq D/W^{1/3} \leq 0.58$. Equation 3.48 is corrected for increasing water depth proportional to $D^{0.7}$ to that for $D/W^{1/3} = 0.5$, i.e., yield is held constant but water depth is increased to maintain geometrical similarity of the wave systems. The water depth required is D = 1,200 feet.

$$H_1 R_1 = 4.96 \times 10^5 \times \left(\frac{1{,}200}{160}\right)^{0.7} = 20.3 \times 10^5\,\text{ft}^2 \tag{3.49}$$

$$\text{for } W = 7\text{ Mt},\ D/W^{1/3} = 0.50,\ R/W^{1/3} = 10$$

Comparison of Equation 3.49 with Equations 3.44 and 3.45 indicates that H_1R_1 is proportional to $W^{1/2}$ for $R/W^{1/3} = 10$ and between W = 20 kt and W = 7 Mt. If the wave height is considered to be proportional to $D^{1/2}$ instead of $D^{0.7}$, Equation 3.49 becomes

$$H_1 R_1 = 13.6 \times 10^5\,\text{ft}^2 \tag{3.50}$$

$$\text{for } W = 7\text{ Mt},\ D/W^{1/3} = 0.50,\ R/W^{1/3} = 10$$

Comparison with Equations 3.44 and 3.45 indicates the $D^{0.7}$ scaling gives the better results. Referring to Plate 25 of Reference 11, the range of $R/W^{1/3}$ for this comparison can logically be extended to $5 \leq R/W^{1/3} \leq 35$, since the slope of the two inner curves (100 and 60 feet, scaled depth) was determined by comparatively little data compared to the two outer curves (30 and 200 feet, scaled depth). The above comparisons indicate that the first-crest scaling of $H_1R_1 \propto W^{1/2}$ rather than $H_1R_1 \propto W^{7/12}$ is applicable for nuclear yield ranges between 20 kt and 7 Mt and for ranges of $R/W^{1/3} \leq 35$. As noted earlier, the Castle data alone will not support conclusions about the $W^{7/12}$ versus $W^{1/2}$ scaling as the varied geometries and associated efficiencies of wave generation cannot be adequately evaluated to permit isolation of the yield exponent for the 7-to-15-Mt range involved. In addition, the lagoon effects upon the propagating waves are suspected of introducing a limiting scatter in the recorded data. A scaling comparison as above between Crossroads Baker and Castle 5 results in the following equations. Crossroads data scaled up to the Shot 5 yield by $W^{1/2}$, Equation 3.45 gives

$$H_1 R_1 = 29.6 \times 10^5\,\text{ft}^2 \tag{3.51}$$

$$W = 13.5\text{ Mt},\ D/W^{1/3} = 0.50,\ R/W^{1/3} \leq 35$$

Assuming that an average depth of wave generation for Shot 5 was 200 feet, an increase of

40 feet over the generation depth for Shot 4, the radius-wave height product from the Shot 5 data with $H_1 \propto D^{0.7}$ is

$$H_1R_1 = 36.4 \times 10^5\,ft^2 \tag{3.52}$$

$$W = 13.5\text{ Mt},\ D/W^{1/3} = 0.5,\ R/W^{1/3} \leq 35$$

As before, the results are in favor of $W^{1/2}$ scaling and not $W^{7/12}$. This HR product (Equation 3.52) varies inversely as the assumed water depth of generation. An assumed D of 240 feet instead of 200 feet results in

$$H_1R_1 = 32 \times 10^5\,ft^2 \tag{3.53}$$

Shot 5 was in the same location as Shot 4. The crater survey made between Shots 4 and 5 is not available; however, the bottom topography prior to Shot 4 and after Shot 5 is available. That portion of the Shot 5 crater attributable to Shot 4 can be interpreted to mean that the increased water depth directly underneath or very close to the barge does affect the wave height and energy when a significantly higher yield is considered. In other words, the yield of Shot 5 was sufficiently greater than that of Shot 4 that one might suspect that the additional water occupying the earlier crater was lost to the lagoon and would not enter into increasing the wave height. In view of the above depth-effect comparison and the increased wave effect, this does not appear to be the case. It is also noted that the tolerance on the Shot 5 yield is ± 1 Mt, and this alone restricts conclusions about the water depth effect in the zone of generation.

The high-explosive results of Reference 11 give scaling equations for extrapolation into the nuclear range. It is desirable to scale to the yield of Shot 4, using the derived relationships from this reference. Two alternatives for this projection are available:

1. The wave height versus range can be scaled from a scaled high-explosive water depth of $D/W^{1/3} = 0.064$ (a 20-kt weapon in approximately 30 feet water) to the Shot 4 yield by equations developed from Reference 11, high-explosive data only. The maximum charge size used in the Reference 11 tests was 2,000 pounds of TNT in a scaled depth near that for Shot 4.

2. The relationship of wave height to range can be scaled from yield data up to and including Crossroads Baker yield by a scaling relationship developed by Reference 11 for $D/W^{1/3} = 0.585$ (20 kt in 200 feet water). The equation to be used in this instance was derived from the high-explosive data of Reference 11, averaged with all other high-explosive data available as well as the Crossroads data. This equation is for data obtained in scaled depths in the range of $D/W^{1/3}$ from 0.5 to 0.6 and the comparison with Castle Shot 4 data would require, as before, a transfer of Shot 4 data to approximately 1,400 feet (generation depth) with $H_1 \propto D^{0.7}$ for a comparison at $D/W^{1/3} = 0.585$.

Comparison 1 is considered first. For $D/W^{1/3} = 0.064$ it is necessary to extrapolate the data of Plate 27, Reference 11, from a scaled depth of $D/W^{1/3} = 0.088$.

$$H_1W^{1/4} = 0.30\left(R_1/W^{1/3}\right)^{-0.7},\ \text{Reference 11 } D/W^{1/3} = 0.088 \tag{3.54}$$

$$H_1W^{1/4} = 0.22\left(R_1/W^{1/3}\right)^{-0.7},\ D/W^{1/3} = 0.064 \tag{3.55}$$

or,

$$H_1R_1^{0.7} = 0.22W^{0.48},\ D/W^{1/3} = 0.064 \tag{3.56}$$

$$H_1R_1^{0.7} = 0.163 \times 10^5\,ft^2 \text{ for } W = 7\text{ Mt},\ D/W^{1/3} = 0.064 \tag{3.57}$$

This is to be compared with Equation 3.48, which is

$$H_1R_1 = 4.96 \times 10^5\,ft^2,\ W = 7\text{ Mt},\ D/W^{1/3} = 0.064$$

The wave heights from Equations 3.57 and 3.48 are given in Table 3.2a. The 86,000-foot range is that of Site Nan.

Considering that the high-explosive data is scaled from 1 to 7 × 10^6 in yield, the close agreement is surprising. Assuming that the $H_1R_1^{0.7}$ charge size scaling of Reference 11 is in error by an insignificant amount such that the scaled wave height agrees with the measured data at the 21,000-foot range, the spread of the measured $H_1 \propto 1/R_1$ with the scaled $H_1 \propto 1/R_1^{0.7}$ is given in Table 3.2b.

Since the experimental wave height at 86,000 feet includes an indeterminate positive reflectance

TABLE 3.2a SCALED WAVE HEIGHT VERSUS RANGE (ALL IN FEET)

	$D/W^{1/3}$ = 0.064	D = 160 ft	W = 7 Mt
Range	21,000	59,000	86,000
H_1 (Experimental)	23.6	8.4	5.7
H_1 (Scaled from Reference 11)	15.5	7.6	5.7
Difference	−8.1	−0.8	0

TABLE 3.2b SCALED WAVE HEIGHT VERSUS RANGE (FEET)

	$D/W^{1/3}$ = 0.064	D = 160 ft	W = 7 Mt
Range	21,000	59,000	86,000
H_1 (Experimental)	23.6	8.4	5.7
H_1 (Scaled from Reference 11)	23.6	11.3	8.7
Difference	0	+2.9	+3.0

factor, the +3 feet difference of Table 3.2b indicates that the scaled wave heights of Table 3.2a compare most favorably with experimental data. But the 21,000-foot-range experimental data of Table 3.2a is that of Station 163.02, and this record (see Figure B.3) is one of the best in quality, so the probability of the measured wave height being in error by plus 8 feet is very remote. The apparent conclusion is that H_1 is decaying proportionally to $1/R_1$ in Bikini Lagoon for this shot. The yield scaling from 2,000 pounds of TNT as set forth by Reference 11 matches the range of observed wave heights very well.

When Comparison 2 is considered, the averaged curve for $D/W^{1/3}$ = 0.585, D = 200 feet, and Z/D = −0.3 to −0.7 (Z = depth of charge submergence) is

$$H_1/W^{1/4} = 1.74\left(R_1/W^{1/3}\right)^{-0.80} \text{ from Reference 11, Plate 27} \quad (3.58)$$

or

$$H_1R_1^{0.8} = 1.74\ W^{0.52},\ D/W^{1/3} = 0.585 \quad (3.59)$$

$$H_1R_1^{0.8} = 3.28 \times 10^5,\ D/W^{1/3} = 0.585,\ \text{and } W = 7\text{ Mt} \quad (3.60)$$

$$H_1R_1 = 4.96 \times 10^5 ft^2,\ D/W^{1/3} = 0.064,\ \text{and}\ W = 7\ Mt \quad \text{(Equation 3.48)}$$

$$H_1R_1 = 22.8 \times 10^5 ft^2,\ D/W^{1/3} = 0.585,\ \text{and}\ W = 7\ Mt$$
$$\text{by}\ H_1 \propto D^{0.7},\ \text{and}\ D = 1{,}410\ ft \quad (3.61)$$

Equation 3.61 is compared with Equation 3.60 in Table 3.3.

The scaled values of wave heights at all ranges are substantially greater than those from the experimental data. The comparison in Tables 3.2a, 3.2b and 3.3 involves two of the variables under investigation over ranges not supported by experimental data: (1) the W scaling to bring the high-explosive and Bikini Baker data to the 7 Mt value and (2) the $H_1 \propto D^{0.7}$ scaling to transfer the experimental data to the required scaled depth for comparison. In the first approach, $H_1 \propto D^{0.7}$ was utilized in the yield range covered by the high-explosive data and, therefore, is considered to verify the $W^{1/2}$ scaling indicated earlier. In view of this, the comparison, Page 27, of Equation 3.45 with Equation 3.49 strengthens the applicability of the $H_1 \sim D^{0.7}$ relationship. Both of these D and W exponents give results within the range of available data in the comparison of Equations 3.51 and 3.53.

TABLE 3.3 SCALED WAVE HEIGHT VERSUS RANGE (FEET)

	$D/W^{1/3} = 0.585$	D = 1,410 ft	W = 7 Mt
Range	21,000	59,000	86,000
H_1 (Experimental) (Equation 3.61)	108	38.7	26.5
H_1 (Scaled from Reference 11) (Equation 3.60)	208	54.0	40.2
Difference	+ 100	+ 15.3	+ 13.7

With increased confidence in the $W^{1/2}$ and $H \propto D^{0.7}$ scaling, the differences in wave heights in Table 3.3 are accountable to the coefficient and exponent of W in Equation 3.59 (reference Equations 3.59 and 3.56 when compared at the same $D/W^{1/3}$ within the range of Reference 11 data). A review of the effect of averaging the data of various sources to develop Equation 3.58 revealed that if a similar equation had been based upon Reference 11 high-explosive data alone, the scaled wave heights of Table 3.3 would have been in much-closer agreement.

The indicated exponents resulting from the foregoing comparisons suggest revisions of the model and associated assumptions examined earlier in this section. This is postponed in anticipation of additional experimental data (WT-1308) which will be applicable to the Castle conditions of generation.

In summary, the limited amount of nuclear data available for this report indicates that charge weight to the one-half power is related to the first wave product (H_1R_1) when scaling high explosive and nuclear shallow water waves. The wave height (H_1) varies inversely as the range to the first power for Bikini Lagoon waves of Operation Castle. The wave height of the first wave is directly proportional to water depth in the zone of generation to the 0.7 power. While the large difference in yield values used in obtaining these results tends to improve the reliability of such conclusions, the verification of their applicability for yields other than those investigated will have to be supported by additional experimental data.

3.5 SCALING TECHNIQUE FOR CASTLE WAVES

In view of the above considerations and indicated scaling relationships, the Castle data is fitted to Equation 3.40, where n = 1, m = 1, and the results are presented in Table 3.4. The depth term has been omitted because of the difficulty in estimating values for the different geometries of generation. The averaged K values for Shots 1 and 2 are in good agreement, whereas those for Shots 4 and 5 are progressively higher. It is apparent that the increased wave height between Shots 4 and 5 results from increased water depth in the Shot 4 crater. The individual records indicate that reflection alters the first-crest wave heights near islands, but the experi-

TABLE 3.4 FIRST-CREST SCALING

W = Equivalent charge weight in megatons. ϕ = Breach factor for comparison of reef and barge shots. Estimated central angle of breach in radians. Maximum = π. ρ = Crater density factor. Estimated ratio of density of material initially occupying crater volume to water. R = Radius of height versus time measurement. Estimated path of travel. H_c = First crest height, ft, in 60 feet of water. K = A constant of proportionality.

Station Number	Range $R \times 10^{-5}$	First Crest Height H_c	$H_cR \times 10^{-5}$	Yield	Breach Factor ϕ	Crater Density Factor ρ	First Crest Scaling Constant K §	First Crest Potential Energy per Unit Wave Front Length E	First Crest Potential Energy* $2\pi E R \times 10^{-17}$	First Crest Total Energy † ‡
	ft	ft		Mt	radian			ft × ft water × sec	erg	pct of yield
Shot No. 1										
162.01	1.22	1.1	1.34	15.0 ± 0.5	1	2.5	0.97	45.7	23.1	0.0006
163.04	1.05	1.4	1.47	15.0 ± 0.5	1	2.5	1.06	75.2	32.8	0.0009
163.03	0.90	1.3	1.17	15.0 ± 0.5	1	2.5	0.85	23.5	8.8	0.0002
							Avg 0.96			
Shot No. 2										
162.01	1.22	1.9	2.32	11.0 ± 0.5	1	1	1.24	117.9	59.8	0.002
163.04	1.05	2.5	2.62	11.0 ± 0.5	1	1	1.40	52.2	22.8	0.0008
163.03	0.90	1.6	1.44	11.0 ± 0.5	1	1	0.77	55.8	20.8	0.0008
162.02	0.79	2.9	2.29	11.0 ± 0.5	1	1	1.22	90.2	29.5	0.001
163.02	0.66	2.2	1.46	11.0 ± 0.5	1	1	0.78	257.4	71.0	0.003
							Avg 1.08			
Shot No. 4										
162.04 S	0.86	3.4	2.92	7.0 ± 0.3	π	1	1.10	180	64.3	0.003
163.05	0.76	5.2	3.95	7.0 ± 0.3	π	1	1.49	649	204	0.012
163.04	0.60	5.2	3.10	7.0 ± 0.3	π	1	1.17	328	66	0.004
162.03	0.59	5.0	2.92	7.0 ± 0.3	π	1	1.10	454	110	0.006
163.02	0.21	14.0	2.98	7.0 ± 0.3	π	1	1.13	1,530	135	0.008
							Avg 1.20			
Shot No. 5										
162.04 S	0.86	7.0	6.02	13.5 ± 1.0	π	1	1.64	—	—	—
163.05	0.76	7.9	6.00	13.5 ± 1.0	π	1	1.63	724	228	0.007
163.02	0.21	28.0	5.97	13.5 ± 1.0	π	1	1.62	3,060	270	0.008
							Avg 1.63			

* Average first crest velocity = 75 ft/sec

† Approximation: Potential energy = kinetic energy, total energy = sum of two

‡ One gram TNT = 1,300 calories

§ $K = H_cR\,(\pi\rho/W\phi)^{1/3}$

mental values have been entered in the table without any attempt to compensate for this effect. At such points there must be a reflection-amplification factor with limits of 1 and 2. Considering all the factors that probably influenced and altered the generation and propagation of the Castle water waves, it is felt that the average K values presented in Table 3.4 permit a scaling technique that can be utilized in prediction of first-crest heights for tests having geometrically similar conditions of generation and the same range of yields. Wave heights for lagoon tests in other depths of water would require a correction for the water-depth effect. The indication is that this correction is proportional to water depth to the 0.7 power.

3.6 WAVE ENERGY

The potential energies of the first crests are given in Table 3.4. These values were determined by planimetering the recorded wave profiles at various stations, calculating the potential energy of the water mass above mean tide stage, and assuming radial symmetry, applying this to 360 degrees of arc. The total energy in the first crest (potential plus kinetic) can be approximated by doubling the potential energy as derived above, except near a reflecting boundary. The assumption of radial symmetry about 360 degrees implies that if the zero points were located such that the conditions of wave generation in all directions were identical to those in the direction in which the wave measurement was recorded, the wave energy and height would be the same at identical ranges and water depths in any direction. Actually, the arc of symmetry for wave generation and early propagation for the two shot locations is substantially different. From Figures 3.2 and 3.3 it can be visualized that energy dispersion in the early propagation phase for Shots 1 and 2 is restricted to approximately 120 degrees of arc, whereas Shots 4 and 5 have slightly over 190 degrees of restriction.

More specifically, the 360-degree assumption presumes (1) the energy partition and absorption per unit of arc to the material about the water-coral crater is constant and (2) the absorption of wave energy along the lagoon reefs is at the same rate as energy defraction along the arc of a radiating wave. As already noted for waves traveling toward Site How, a coral reef is selective in which portion of the wave system energy it absorbs. Crest energy is trapped and absorbed upon the reef, whereas trough energy is returned to the deeper lagoon waters. It has to be assumed that the resultant of this selectivity allows the second condition, above, to prevail.

The observed scatter in the energy values of Table 3.4 occurs predominately as a result of reflection. The theoretical influence of reflection on potential energy varies between a factor of 1 and 4, and it is seen that the energy values do not exceed this scatter. They do, however, give an indication (to a first order) of the relative energy imparted to the first water wave by the four principal shots.

It should be noted that the proportion of yield energies in the first crests is very small, averaging about one part in 20,000 for the lagoon shots and one part in 100,000 for the reef shots. Total energy in the train probably is not more than five times this quantity. (Operation Wigwam produced waves of approximately one part in 60 of the yield.)

3.7 INUNDATION

The progressive crest diagrams (Figures 3.2 and 3.3) give an indication of reef and island areas in Bikini Lagoon susceptible to concentration or reduction of wave energy and, considering the possible sources of reflected wave energy, point up the complex pattern of resultant shore-line wave action. As indicated in discussing first-crest scaling techniques, generalized estimates of wave performance that rely solely on observed wave action on individual island and reef areas can be misleading. For example, heavy inundation in the Site George reef area could be expected from waves originating in the Site Charlie area. For shots located south of Site Dog, the reflected first crests from Sites Fox and Tare-Oboe undoubtedly are refracted in the direction of the Nan-How reef and time-wise follow only a few minutes behind the first crest traveling directly across the lagoon. The records of wave action at various stations shortly after passage of the first crest are complicated by these mechanisms. This is indicated by examination and comparisons of the more-distant stations' records with those at closer range. For the closer stations, the observed interference occurs at a later time in the progressive wave train. These progression diagrams also indicate the pumping action of incident wave crests along the George-How and How-Nan reefs, which must result in a lowering of the lagoon water level. It can be surmised that this results in a reflected trough and the formation of a long-period, low-amplitude crest that enters the lagoon through the Oboe-Nan channel. Both of these add to the already confused wave pattern. This temporary decrease in water level adjacent to the George-How reef is detected following the first crests at stations near this area for all shots.

Following the shore action of the first crests, the succeeding waves and any resultant inundation are dependent in both magnitude and duration upon the phase arrival of reflected and refracted first crests and troughs from other areas of the lagoon. It is the pattern of wave arrival that determines the extent of damage and inundation to shore installations. Prediction of these patterns becomes complex and unreliable. Certain areas of the lagoon are more susceptible to this type

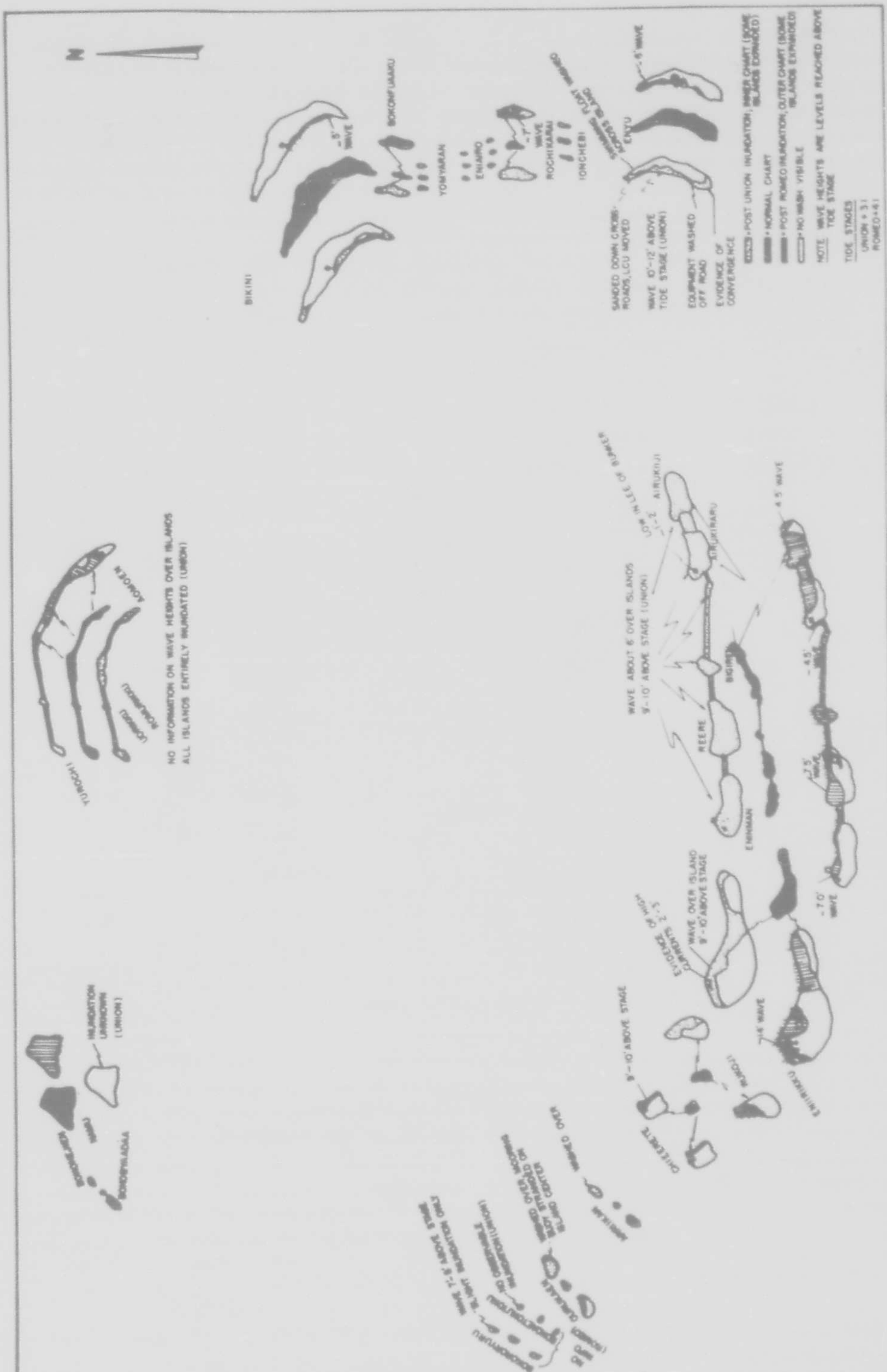


Figure 3.5 Inundation Castle shots.

of amplification than are others for a given shot location. In Bikini Lagoon, the probability of high in-phase amplification must be greater for waves traveling the east-west direction than the north-south. This is to say, in a very approximate manner, that the probability of maximum inundation and shore-line damage will occur with the first crest for land areas on the shorter axis of the lagoon. The chance of maximum inundation occurring as a result of a later wave increases for areas on the longer lagoon axis. Inundation at Site Nan was the result of a combination of direct and reflected wave action. Minor inundation occurred at Site How because the George-How reef absorbed the first, and succeeding, wave-crest energy. Inundation in the Oboe-Alpha area was a result of first-crest height and period.

The results of postshot inundation surveys for Shots 2 and 4 are given in Table 3.5 and Figure 3.5. Values from the percentage of land area inundated were obtained from on-site measurements of the extent of water penetration into the islands. The tide stages are given in Figure 3.5.

TABLE 3.5 INUNDATION (SITE AREA COVERED BY WATER WAVE)

Site	Land Area		Area Covered	
			Shot 2	Shot 4
	10^6 ft^2	acre	pct	pct
Oboe	4.35	100	47	100
Peter	—	—	—	—
Roger	0.40	9.2	90	100
Sugar	2.66	61.0	34	100
Tare	4.22	97.0	41	100
Uncle	91.9	211.0	49.5	51.5
Victor	1.44	33.1	46.8	63
William	1.38	31.7	20.6	27.4
Yoke	0.12	2.8	74	100
Zebra	0.36	8.3	21	100
Alpha	0.28	6.4	Negligible	Negligible
Bravo	0.28	6.4	—	18
Able	—	—	—	—
Baker	—	—	—	—
Charlie	4.36	100	100	—
Dog	0.91	21	0	100
Easy	0.24	5.5	0	100
Fox	1.55	35.6	88	100
George	0.96	22	70.5	100
How	24.4	560	12.2	15.3
Nan	12.5	287	30.6	42
Item	0.20	4.6	55.5	100
Jig	0.20	4.6	0	100
Love	0.51	11.7	71	100
Mike	0.13	3.0	0	100

Since the shots for which data is available were in different locations and had significantly different yields, it is difficult to make a direct comparison of the data. Reference to the first-crest energies given in Table 3.4 indicates the energy contained in waves from Shot 4 to be from two to three times that from Shot 2. The extent of water penetration of the islands must also be a function of the incident angle of the advancing waves to the shore line. Increased wave energy and, possibly, the slightly different approach angle of waves from Shots 2 and 4 resulted in the increased inundation of the Tare-Oboe Complex from Shot 4.

Comparative inundation at Site Nan should be more a direct indication of the relative wave energy, since the direction of approach is essentially the same for the waves from both shots. Site How had little increase in inundation for the two shots under consideration because of its protected location. The data indicates that Site William is partially protected from lagoon wave action. Site Alpha is extremely well protected from wave action because of the extensive lagoon reef. Because of the many complexities, inundation can, at the present, be only qualitatively related to wave height or wave energy.

Chapter 4
CONCLUSIONS and RECOMMENDATIONS

4.1 CONCLUSIONS

In nearby regions, destructive water waves were generated by thermonuclear explosions over shallow water.

The resultant significant water waves were generated in a central region of 2 miles radius or less.

Water wave action accompanying the higher-yield tests may result from two mechanisms: (1) the fallout of the coarse debris and water and (2) the direct impulse to the water mass. In the majority of tests to date, waves as a result of the second mechanism have obscured those of the first, which are much lower in amplitude and longer in period than those of the second.

Water waves resulting from Castle tests were complex, but for successive tests at the same ground zero, they were similar in time history at the same point of observation.

It appears that the density of the medium in which the crater was formed, when directly linked to water, influenced wave height by its inverse one half power.

It appears that the controlling water depth of wave generation is that depth very near and directly under the shot barge. This is indicated by the comparison of the water waves resulting from Shot 4 and the much-larger Shot 5, which was fired over the Shot 4 crater.

It appears that explosions that occur in an independent basin, communicating to a larger basin through a breach, produce waves in the larger basin whose heights are reduced by the square root of the ratio of the angular opening of the breach to the total angle of exposure of the larger basin.

After the passage of air shock wave, long-period seiche-like oscillations were recorded up to the time of arrival of the first impulsively generated crest. These pressure changes appear to represent real water-level changes. Although similar waves have been observed from high-explosive tests, the mechanism of their formation is at present unexplained.

Refraction and reflection of resultant waves against a reef or shore line along its path can significantly reduce or amplify its destructive capabilities at its termination. In Bikini Lagoon and for the Castle tests, Site How is an example of a protected island, whereas Site Nan is an example of a location highly susceptible to amplified inundation. Site Alpha, although exposed to direct approach of the larger waves, was well protected because of its extensive lagoon reef.

For yield values in the range of Castle tests and for Bikini Atoll island sites where focusing effects and reflection-refraction of adjacent lagoon topography is a minimum, heaviest inundation and shore-line destruction can be expected to coincide with the first crest. For less-direct paths, the highest wave is associated with reinforcement from reflected components.

A partially empirical equation can be used in prediction of first-crest wave heights as a function of range for shot locations and yields similar to those of Castle.

Times of arrival of the first crest for tests in Bikini Lagoon fit $V = \sqrt{gD}$, where D is an average depth of 174 feet and V is wave velocity.

The energy in the generated wave trains was on the order of one part in 5,000 of yield for the two open lagoon tests (Shots 4 and 5) and one part in 20,000 of yield for the two tests on the lagoon reef. (Shots 1 and 2.)

First-crest heights for Shots 4 and 5 decreased proportionally to range to the first power.

Crossroads Baker results predict the Shot 4 first-wave height when scaled to the Shot 4 yield by $W^{1/2}$, and wave height is inversely proportional to range to the first power and proportional to water depth to the 0.7 power.

4.2 RECOMMENDATIONS

Further study of open-lagoon water-wave-generation processes in the range from 0.5 to 5.0 miles for yields from 5 to 11 Mt should be made. Additional water-wave data should be secured for these ranges to assist in assigning source conditions to the mathematical models designed to describe the complete wave system.

Additional data should be secured for comparison and for information to lead to an understanding of the close-in water-wave-generating processes of land shots (no breaching) and reef shots (partial breaching).

A further study of refraction and reflection effects should be made. It is apparent that these effects alter amplitudes and periods of an advancing wave train and affect its inundation capabilities. An effort should be made to define the conditions determining areas in which above-average inundation (for a given wave train) can occur with the objective of predicting relative shore-line damage at similar test or operational sites.

Appendix A
DATA REDUCTION

The Mark IX wave-gage transducers used at Sites Nan and How contained internal capillary orifices for nearly complete attenuation of tidal changes in water level. Where significant to the data, the longer-period waves were graphically corrected for this tidal leak. All other instrumentation was of the absolute-pressure type. Calibrations of installations made in situ were by raising and lowering the transducers a measured amount. The attenuation of surface-wave pressures at the transducer depth for installed depths and measured wave periods is negligible. The original traces, corrected for any instrumentation characteristics, represent the true surface-wave height at the place of measurement.

In order to have a common water depth for comparison of surface wave amplitudes, amplitudes at the various depths of measurement were adjusted to a water depth of 60 feet. This depth for comparison is a change from that used in the preliminary report and is selected in anticipation of integration with data from the Redwing shore stations, whose transducers were purposely set in 60 feet of water. In the Castle preliminary report a "shallow water" wave height was defined as a wave height in water whose depth was equal to the wave height. Green's Law was utilized in this transfer, even though experimental evidence about the effect upon wave height of a shoaling bottom indicated that the applicability was limited to water depths substantially greater than the wave heights involved. As wave data from the deeper instrument locations is less subject to reflectance effects, it is felt that the transfer of these values to 60 feet, rather than to a "shallow water" depth as done previously, reduces data scatter accountable to the techniques of handling. Experimental data in Reference 9 can be interpreted to indicate that for a bottom condition of gradual shoaling and a ratio of initial wave amplitude to shelf water depth of approximately 0.1 or less, Green's Law will give an adjusted final amplitude accurate to within approximately 4 percent. However, other data from this same reference is interpreted to show that, in general, Green's Law does not apply. These tests were two-dimensional, and the significant variables involved were the bottom slope, depth ratios, and the final wave height to final depth ratio. Acknowledging the possible errors introduced, Green's Law is utilized in the analysis of Castle data.

The transfer of near-shore data (approximately 20 feet water depth) to the 60-foot comparison depth by Green's Law is highly questionable, but since these measurements are influenced by indeterminate reflectance factors, the selection of 60 feet is considered an improvement over the former "shallow water" reference. For the Mark VIII and Mark IX shore installations, the application of Green's Law resulted in decrease in observed amplitude, whereas for the central lagoon installations, this transfer resulted in increased amplitudes.

For central-lagoon installations, where the transducer was installed atop a coral head of suitable depth, the surface waves were assumed to be unaffected by the presence of the coral head, since the circumference of the coral heads at the base was much less than one half the wave length. Depth of water used in transferring waves measured from coral head sites to 60 feet depth was the average depth within a radius of 3,000 feet of the coral head.

The records from the self-contained, spring-escapement-driven wave units employed at central lagoon sites were discontinuous during the ground-shock and positive-overpressure phases of the shot. The instruments were pretimed to start minutes prior to zero time without a provision for accurately marking the absolute time of initiation. After the passage of the positive-overpressure phase, these units accurately recorded the pressure-time history. Zero time for these records was determined by inserting the positive (half period) portion of the overpressure, as measured at the nearest shore station, ahead of the recorded valid negative-overpressure phase and assigning to the positive peak, so inserted, the calculated travel time of the overpressure peak from ground zero to the station site.

Appendix B

WAVE HEIGHTS as a FUNCTION of TIME at FIXED RANGES

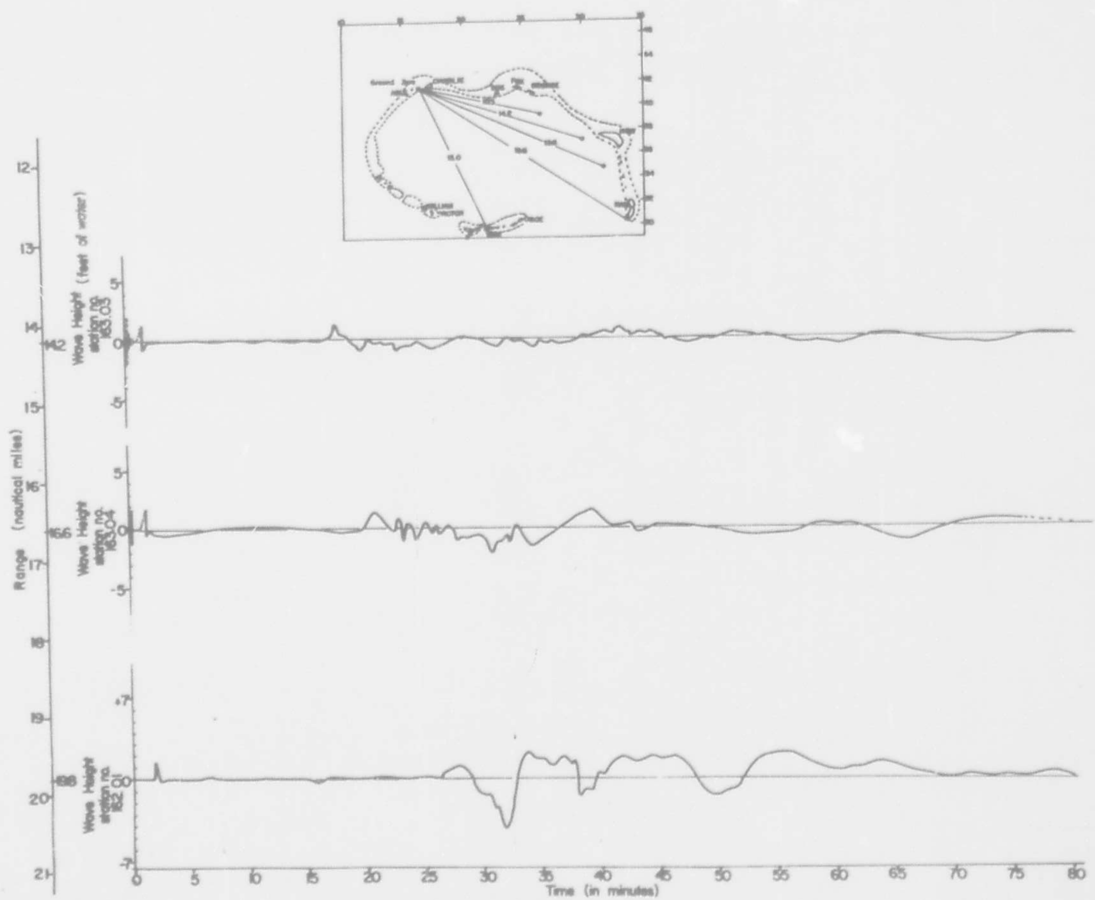


Figure B.1 Wave height versus time at various ranges, Shot 1.

Figure B.2 Wave height versus time at various ranges, Shot 2.

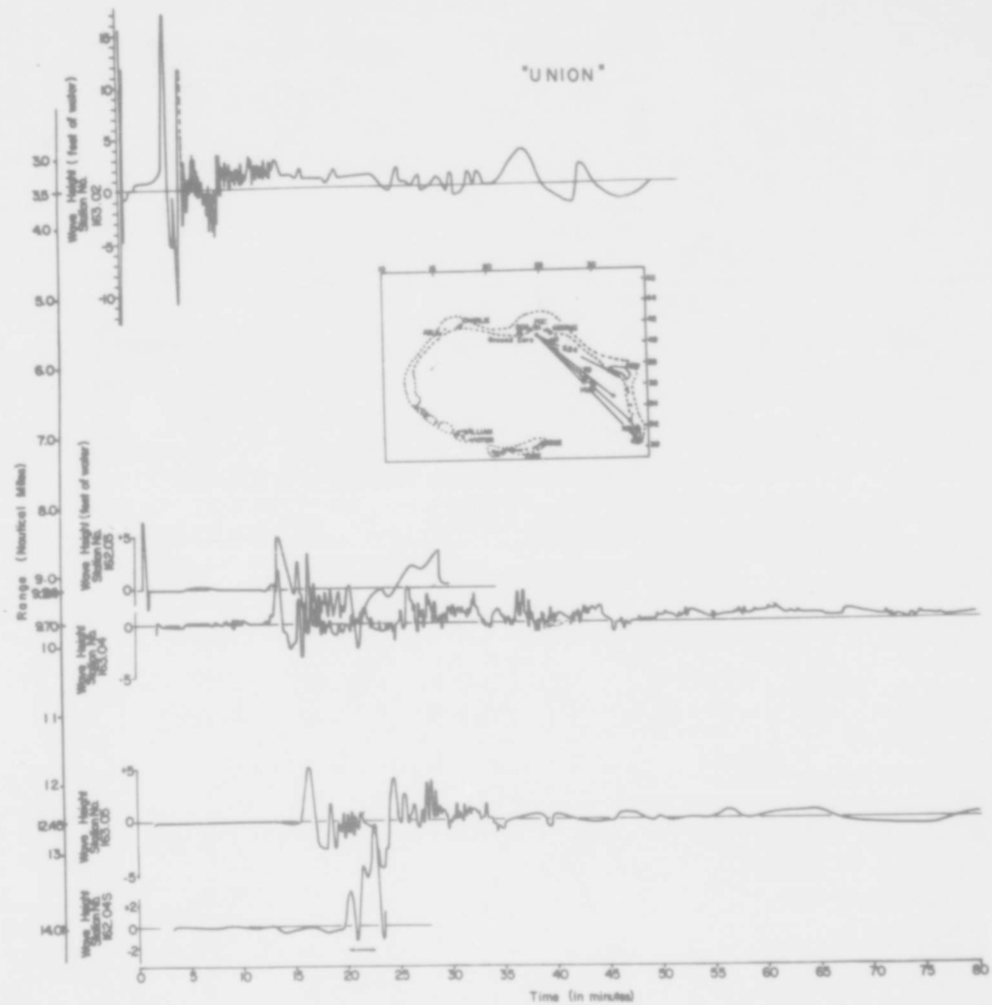


Figure B.3 Wave height versus time at various ranges, Shot 4.

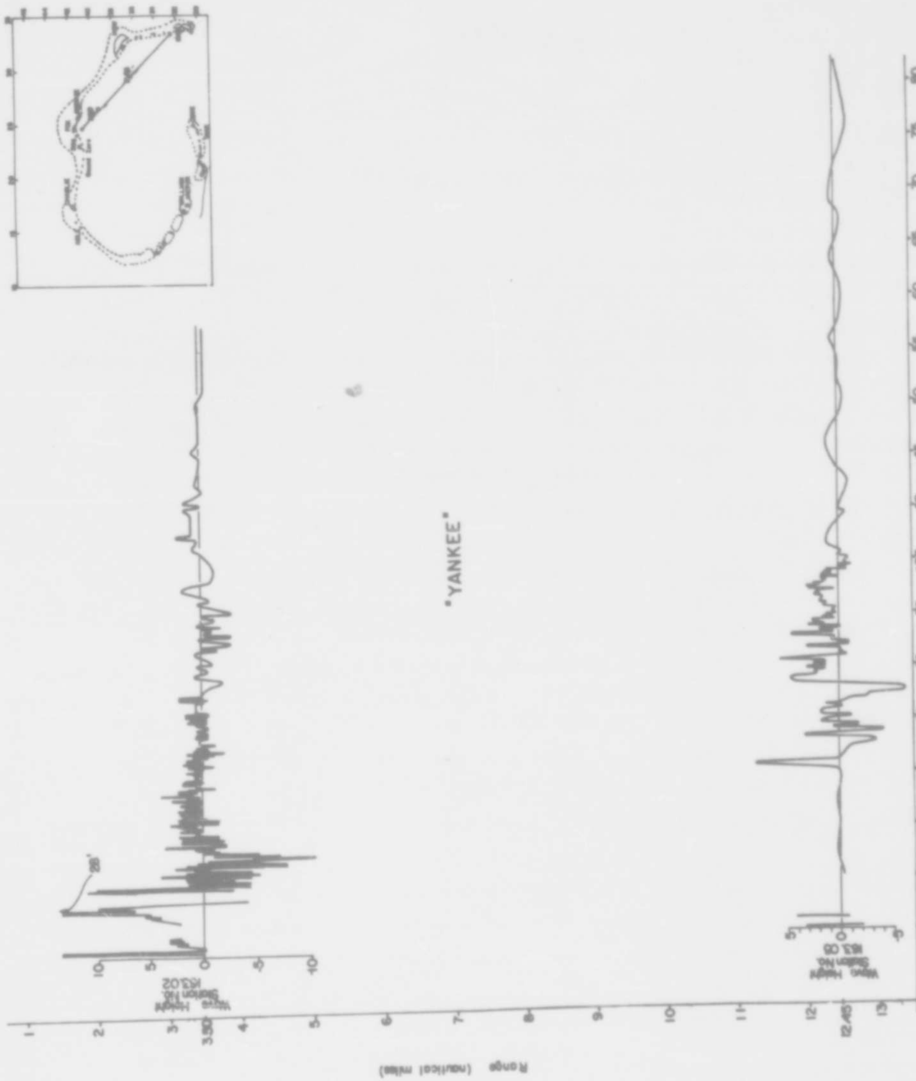


Figure B.4 Wave height versus time at various ranges, Shot 5.

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7- 9 Commanding General, U.S. Continental Army Command, Ft. Monroe, Va.
10 Director of Special Weapons Development Office, Headquarters CONARC, Ft. Bliss, Tex. ATTN: Capt. Chester I. Peterson
11 President, U.S. Army Artillery Board, U.S. Continental Army Command, Ft. Sill, Okla.
12 President, U.S. Army Air Defense Board, U.S. Continental Army Command, Ft. Bliss, Tex.
13 Commandant, U.S. Army Command & General Staff College, Ft. Leavenworth, Kansas. ATTN: ARCHIVES
14 Commanding General, Chemical Corps Training Comd., Ft. McClellan, Ala.
15 Commanding General, The Engineer Center, Ft. Belvoir, Va. ATTN: Asst. Cmdt, Engr. School
16 Director, Armed Forces Institute of Pathology, Walter Reed Army Med. Center, 625 16th St., NW, Washington 25, D.C.
17 Commanding Officer, Army Medical Research Lab., Ft. Knox, Ky.
18 Commandant, Walter Reed Army Inst. of Res., Walter Reed Army Medical Center, Washington 25, D.C.
19- 20 Commanding Officer, Chemical Warfare Lab., Army Chemical Center, Md. ATTN: Tech. Library
21 Commanding General, Engineer Research and Dev. Lab., Ft. Belvoir, Va. ATTN: Chief, Tech. Support Branch
22 Director, Waterways Experiment Station, P.O. Box 631, Vicksburg, Miss. ATTN: Library
23 Commanding General, Aberdeen Proving Grounds, Md. ATTN: Director, Ballistics Research Laboratory
24 Director, Operations Research Office, Johns Hopkins University, 6935 Arlington Rd., Bethesda 14, Md.
25 President, Beach Erosion Board, Corps of Engineers, U.S. Army, 5201 Little Falls Rd., N.W., Washington 16, D.C.
26 Commander-in-Chief, U.S. Army Europe, APO 403, New York, N.Y. ATTN: Opot. Div., Weapons Br.
27 Commander-in-Chief, U.S. Army Pacific, APO 958, San Francisco, Calif. ATTN: Ordnance Officer

NAVY ACTIVITIES

28 Chief of Naval Operations, D/N, Washington 25, D.C. ATTN: OP-03EG
29 Chief of Naval Operations, D/N, Washington 25, D.C. ATTN: OP-31
30 Chief of Naval Operations, D/N, Washington 25, D.C. ATTN: OP-75
31 Chief of Naval Operations, D/N, Washington 25, D.C. ATTN: OP-91
32 Chief of Naval Operations, D/N, Washington 25, D.C. ATTN: OP-922G1
33- 34 Chief of Naval Research, D/N, Washington 25, D.C. ATTN: Code 811
35- 36 Chief, Bureau of Aeronautics, D/N, Washington 25, D.C.
37 Chief, Bureau of Ordnance, D/N, Washington 25, D.C.
38 Chief, Bureau of Ships, D/N, Washington 25, D.C. ATTN: Code 423
39 Chief, Bureau of Yards and Docks, D/N, Washington 25, D.C. ATTN: D-440
40 Director, U.S. Naval Research Laboratory, Washington 25, D.C. ATTN: Mrs. Katherine H. Cass
41- 42 Commander, U.S. Naval Ordnance Laboratory, White Oak, Silver Spring 19, Md.
43 Commanding Officer and Director, Navy Electronics Laboratory, San Diego 52, Calif.
44 Commanding Officer, U.S. Naval Mine Defense Lab., Panama City, Fla.
45- 46 Commanding Officer, U.S. Naval Radiological Defense Laboratory, San Francisco, Calif. ATTN: Tech. Info. Div.
47- 49 Officer-in-Charge, U.S. Naval Civil Engineering R&E Lab., U.S. Naval Construction Bn. Center, Port Hueneme, Calif. ATTN: Code 753
50 Commanding Officer, U.S. Naval Schools Command, U.S. Naval Station, Treasure Island, San Francisco, Calif.
51 Superintendent, U.S. Naval Postgraduate School, Monterey, Calif.
52 Commanding Officer, U.S. Fleet Sonar School, U.S. Naval Base, Key West, Fla.
53 Commanding Officer, U.S. Fleet Sonar School, San Diego 47, Calif.
54 Officer-in-Charge, U.S. Naval School, CEC Officers, U.S. Naval Construction Bn. Center, Port Hueneme, Calif.
55 Commanding Officer, Nuclear Weapons Training Center, Atlantic, U.S. Naval Base, Norfolk 11, Va. ATTN: Nuclear Warfare Dept.
56 Commanding Officer, Nuclear Weapons Training Center, Pacific, Naval Station, San Diego, Calif.
57 Commanding Officer, U.S. Naval Damage Control Tng. Center, Naval Base, Philadelphia 12, Pa. ATTN: ABC Defense Course
58 Director, Naval Air Experiment Station, Air Material Center, U.S. Naval Base, Philadelphia, Pa.
59 Commanding Officer, U.S. Naval Medical Research Institute, National Naval Medical Center, Bethesda, Md.
60- 61 Commanding Officer and Director, David W. Taylor Model Basin, Washington 7, D.C. ATTN: Library
62 Commanding Officer and Director, U.S. Naval Engineering Experiment Station, Annapolis, Md.
63 Commander, Norfolk Naval Shipyard, Portsmouth, Va. ATTN: Underwater Explosions Research Division
64- 67 Commandant, U.S. Marine Corps, Washington 25, D.C. ATTN: Code AO3H
68 Commanding Officer, U.S. Naval CIC School, U.S. Naval Air Station, Glynco, Brunswick, Ga.
69 Chief of Naval Operations, Department of the Navy, Washington 25, D.C. ATTN: OP-25

AIR FORCE ACTIVITIES

70 Assistant for Atomic Energy, HQ, USAF, Washington 25, D.C. ATTN: DCS/O
71 Deputy Chief of Staff, Operations HQ. USAF, Washington 25, D.C. ATTN: Operations Analysis
72- 73 Assistant Chief of Staff, Intelligence, HQ. USAF, Washington 25, D.C. ATTN: AFCIN-3B
74 Director of Research and Development, DCS/D, HQ. USAF, Washington 25, D.C. ATTN: Guidance and Weapons Div.
75 The Surgeon General, HQ. USAF, Washington 25, D.C. ATTN: Bio.-Def. Pre. Med. Division
76 Commander, Tactical Air Command, Langley AFB, Va. ATTN: Doc. Security Branch
77 Commander, Air Force Ballistic Missile Div. HQ. ARDC, Air Force Unit Post Office, Los Angeles 45, Calif. ATTN: WDSOT

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78 Commander, Hq. Air Research and Development Command, Andrews AFB, Washington 25, D.C. ATTN: RDRWA

79- 80 Commander, AF Cambridge Research Center, L. G. Hanscom Field, Bedford, Mass. ATTN: CRQST-2

81- 85 Commander, Air Force Special Weapons Center, Kirtland AFB, Albuquerque, N. Mex. ATTN: Tech. Info. & Intel. Div.

86- 87 Director, Air University Library, Maxwell AFB, Ala.

88 Commander, Lowry AFB, Denver, Colorado. ATTN: Dept. of Sp. Wpns. Tng.

89 Commandant, School of Aviation Medicine, USAF, Randolph AFB, Tex. ATTN: Research Secretariat

90 Commander, 1009th Sp. Wpns. Squadron, HQ. USAF, Washington 25, D.C.

91- 93 Commander, Wright Air Development Center, Wright-Patterson AFB, Dayton, Ohio. ATTN: WCOSI

94- 95 Director, USAF Project RAND, VIA: USAF Liaison Office, The RAND Corp., 1700 Main St., Santa Monica, Calif.

96 Commander, Air Technical Intelligence Center, USAF, Wright-Patterson AFB, Ohio. ATTN: AFCIN-4B1a, Library

97 Assistant Chief of Staff, Intelligence, HQ. USAFE, APO 633, New York, N.Y. ATTN: Directorate of Air Targets

98 Commander-in-Chief, Pacific Air Forces, APO 953, San Francisco, Calif. ATTN: PFCIE-MB, Base Recovery

OTHER DEPARTMENT OF DEFENSE ACTIVITIES

99 Director of Defense Research and Engineering, Washington 25, D.C. ATTN: Tech. Library

100 Chairman, Armed Services Explosives Safety Board, DOD, Building T-7, Gravelly Point, Washington 25, D.C.

101 Director, Weapons Systems Evaluation Group, Room 1E880, The Pentagon, Washington 25, D.C.

102-109 Chief, Defense Atomic Support Agency, Washington 25, D.C. ATTN: Document Library Branch

110 Commander, Field Command, DASA, Sandia Base, Albuquerque, N. Mex.

111 Commander, Field Command, DASA, Sandia Base, Albuquerque, N. Mex. ATTN: FCTG

112-116 Commander, Field Command, DASA, Sandia Base, Albuquerque, N. Mex. ATTN: FCWT

117 Commander, JTF-7, Arlington Hall Station, Arlington 12, Va.

118 Commandant, U.S. Coast Guard, 130[illegible] E. St., N.W., Washington 25, D.C. ATTN: (OIN)

119 Commander-in-Chief, Strategic Air Command, Offutt AFB, Ne[illegible] ATTN: OAWS

120 U.S. Documents Officer, Office of the United States National Military Representative - SHAPE, APO 55, New York, N.Y.

ATOMIC ENERGY COMMISSION ACTIVITIES

121-123 U.S. Atomic Energy Commission, Technical Library, Washington 25, D.C. ATTN: For DMA

124-125 Los Alamos Scientific Laboratory, Report Library, P.O. Box 1663, Los Alamos, N. Mex. ATTN: Helen Redman

126-130 Sandia Corporation, Classified Document Division, Sandia Base, Albuquerque, N. Mex. ATTN: [illegible] J. Smyth, Jr.

131-133 University of California Lawrence Radiation Laboratory, P.O. Box 808, Livermore, Calif. ATTN: Clovis G. Craig

134 Essential Operating Records, Division of Information Services for Storage at ERC-H. ATTN: John E. Hans, Chief, Headquarters Records and Mail Service Branch, U.S. AEC, Washington 25, D.C.

135 Weapon Data Section, Technical Information Service Extension, Oak Ridge, Tenn.

136-165 Technical Information Service Extension, Oak Ridge, Tenn. (Surplus)

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